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Modelling Nuclear Energy Systems with MESSAGE: A User’s Guide

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MODELLING NUCLEAR ENERGY SYSTEMS WITH MESSAGE: A USER’S GUIDE

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FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

One of the IAEA's objectives is to provide integrated services to Member States considering the initial development or expansion of their nuclear energy programmes. Member States have recognized the increasing need to model future nuclear power scenarios in order to develop strategies for sustainable nuclear energy systems, explore opportunities for cooperation and partnerships during the nuclear fuel cycle, and consider how global trends may affect national developments.

To meet this need, the IAEA International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) has developed a framework for the analysis and assessment of transition scenarios to sustainable nuclear energy systems. It includes, as one of the elements, the Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE), an IAEA tool which supports energy analysis and planning, and has been extended for the purpose of nuclear energy system modelling, in particular for material flow analysis to support nuclear energy system assessment.

This publication is the result of joint efforts of the IAEA Planning and Economic Studies Section and the INPRO Section in modelling nuclear energy systems with MESSAGE and applying it in training provided to Member States. The IAEA is grateful to all those who assisted in drafting and reviewing this publication. The IAEA officers responsible for this publication were A. Jalal, G. Fesenko and V. Kuznetsov of the Division of Nuclear Power.

EDITORIAL NOTE

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

As a growing number of States are considering nuclear power to meet future energy needs, the IAEA is expanding its support to help its Member States to evaluate nuclear options. The IAEA helps to ensure that nuclear energy is used in the safest, most secure manner and exclusively for peaceful purposes. Towards this goal, the IAEA stresses the need to plan properly, to build the required human resources and infrastructure, and to adhere to international safety, security and non-proliferation norms.

The timeframe for creating national capacities to introduce nuclear power is long. The commitments related to managing this technology extend over generations. A single nuclear power unit requires 3–4 years of planning and 7–8 years of construction. It can operate for 40–60 years and then has to be decommissioned after its useful life. The entire timeline may cover 80 years. It is therefore vital that the initial planning phase is extremely thorough and includes a detailed evaluation of social, economic, technological and environmental impacts and consequences for the country.

1.1.1. MESSAGE

The Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE) was originally designed as a systems engineering optimization model for medium to long term energy system planning, energy policy analysis and scenario development.[1] Based on the seminal Häfele–Manne model, it was formally developed by the International Institute for Applied Systems Analysis during the 1970s, and enhanced and expanded during the 1980s and 1990s. The IAEA acquired MESSAGE in 2000 and further enhanced it to support detailed evaluation of alternative energy strategies, including the use of nuclear technologies [1.1]. The IAEA also added a user interface to facilitate its application in developing countries. It has been constantly updated and enhanced to enable the analysis of emerging energy issues.

The embedded methodology of MESSAGE is based on the optimization of an objective function under a set of constraints on, for example, resource extraction, fuel availability and trade, new investments, market penetration for new technologies, environmental emissions and waste generation, in order to formulate and evaluate alternative energy supply strategies to meet demand for energy. The backbone of MESSAGE is a mathematical representation of the technoeconomic description of an energy system. This includes the definition of the categories of energy forms considered (e.g. primary energy, final energy and useful energy), the fuels (commodities) and associated technologies that are actually used (e.g. electricity, gasoline, ethanol, coal and district heat), as well as energy services (e.g. useful space heating provided by types of energy technology). Technologies are defined by their inputs and outputs (main and by-products), their efficiency and their variability if more than one input or output exists — for example, with the possible production patterns of a refinery or a pass-out turbine [1.1].

Economic characteristics include investment costs, fixed and variable operation and maintenance costs, imported and domestic fuel costs, estimates of levelized costs and shadow prices. Fuels and technologies are combined to construct energy chains through which energy flows from supply to demand. The model takes into account existing installations, their age and their decommissioning at the end of their operating lifespans. The investment requirements can be distributed over the construction time of a plant and can be divided into different categories to reflect more accurately the requirements of industrial and commercial sectors. The requirements for basic materials and non-energy inputs during construction and operation of a plant can also be accounted for by tracing their flow from originating industries, either in monetary terms or in physical units. For some fuels, ensuring timely availability entails considerable cost and management efforts. Electricity has to be provided by the utility at exactly the same time it is required, and MESSAGE simulates this situation. Environmental aspects can be analysed by keeping track of, or constraining, pollutants emitted by various technologies at each step of the energy chain. This also helps to evaluate the impact of environmental regulations on energy system development.

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[1] For further information, see http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.html.

1.1.2. Extension of MESSAGE capabilities to model an NES

When considering national energy planning, a starting point is the development of a long term strategy based on an holistic evaluation of all future energy supply options that could meet future demand for energy services, according to a State's long term outlook on social and economic development [1.1, 1.2]. If nuclear energy is a preferred option for a State's future energy mix, the strategy should further elaborate the development and deployment of nuclear energy systems (NESs). To assist a Member State in performing analysis of transition scenarios to sustainable NESs [1.3, 1.4], the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) has led the international development of the INPRO Methodology for Nuclear Energy System Assessment [1.5]. NES analysis and assessment can be performed by States with established nuclear programmes to assess the transition from a current fleet of reactors to an NES with innovative technologies, and by States considering, or embarking on, new nuclear power programmes.

A wide range of infrastructure issues needs to be addressed before a State can introduce its first nuclear power plant (NPP). The IAEA Milestones process provides a systematic approach for decision makers developing a national nuclear power programme in the near term [1.6, 1.7]. This approach provides practical guidance in establishing an adequate infrastructure for the first NPP.

In addition to NPPs, an NES includes the complete spectrum of the nuclear fuel cycle [1.1]:

- Mining;
- Milling;
- Conversion;
- Enrichment of uranium and thorium;
- Fuel fabrication;
- Electricity generation and other energy products;
- Reprocessing to recover fissile material;
- Storage of reprocessed fissile material;
- Waste treatment and stabilization;
- Waste repository and final end states for all wastes;
- Associated institutional arrangements.

It is necessary to cautiously address the management of the various steps of an NES and to determine which steps to localize and which technologies to deploy.

Some States seek only the use of nuclear technology, while others seek to develop the entire NES and its related technologies. In both cases, the development of a suitable strategy requires a detailed, quantified analysis of the capacities and timing of the various nuclear facilities to be constructed, the amount of nuclear material to be handled, the volumes and characterization of nuclear waste to be managed, and other requirements for the various steps of the NES. Such an analysis demands mathematical modelling of the NESs, representing all the technical details, performance parameters, materials involved and costs. MESSAGE provides a convenient platform for modelling NESs.

Nuclear technologies with their specific features can be modelled efficiently with MESSAGE. Among other things, the model can help:

(a) To produce a description of the entire NES, with time dependent parameters for long term planning;
(b) To confirm the feasibility of an NES through the correlation and consistency of all NES components, constraints and boundary conditions;
(c) To balance fissile material in a closed fuel cycle and to determine its requirements;
(d) To assist the user in the choice of alternatives by comparing the different options regarding, among other things, the need for fuel, and the volume and toxicity of the waste.

Modelling an NES is quite flexible in MESSAGE, and users can decide which components to include in the model. Each component can be represented in MESSAGE with the necessary details, such as first loading and final unloading of fuel in reactors, cooling time for spent fuel discharged from the reactor, lag and lead time for processes, and losses [1.3]. Nuclear power processes can be taken into account such as changes in the isotopic composition of spent fuel during the cooling time in storage at the NPP or reprocessing lag time due to the radioactive decay of unstable isotopes [1.8]. Nonetheless, MESSAGE has some limitation with regard to taking account of the decay of plutonium and minor actinides in intermediate stocks.

1.1.3. Framework for analysing NES scenarios

The INPRO Collaborative Project Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle (GAINS) has developed an international analytical framework for assessing transition scenarios to future sustainable NESs [1.3, 1.4]. For this publication, the major assumptions and boundary conditions for NESs, as well as data for thermal and fast reactors and their respective fuel cycles, are based on the GAINS analytical framework.

Sample analyses with GAINS used MESSAGE as one of the elements for material flow simulation to support evaluations. Major elements of the analytical framework include [1.4]:

(a) Scenarios for long term nuclear power evolution based on projections from international energy organizations;
(b) A heterogeneous global model to capture different States' policies regarding the back end of the nuclear fuel cycle;
(c) Metrics and tools to assess the sustainability of scenarios for a dynamic NES;
(d) An international database of characteristics of existing and future innovative nuclear reactors and associated nuclear fuel cycles for material flow analysis;
(e) Findings from the analysis of transition scenarios from present nuclear reactors and fuel cycles to future NES architecture with innovative technological solutions.

Sixteen participants from different regions of the world conducted coordinated investigations in contribution to the GAINS final report. The GAINS project defined and evaluated the entire range of NESs and reactor technologies — from the most common systems currently operating, to the systems planned for near to medium term deployment and to the most innovative systems which are in early stages of research and development. The following NESs were examined using MESSAGE [1.3, 1.8, 1.9]:

- A once through fuel cycle;
- A partially closed fuel cycle based on thermal reactors with plutonium mono-recycling;
- A closed fuel cycle based on thermal and fast reactors with plutonium multi-recycling;
- The role of the research, development and demonstration cost component in the transition to a commercially viable, innovative NES, based on a closed fuel cycle with fast reactors;
- Modelling global NESs in terms of fuel cycle technology groupings;
- A thorium fuel cycle based on thermal and fast reactors with spent fuel reprocessing and plutonium/^{233}U recycling;
- Molten salt reactors and accelerator driven systems with the inclusion of minor actinide multi-recycling.

GAINS project participants have performed cross-check assessments, comparing the results of different codes using the project in order to ensure the credibility of the analysis results. Cross-check studies using IAEA and national tools have been an essential step in harmonizing Member States' analytical tools in support of decision making related to long term nuclear strategy and energy planning. The cross-check calculations were performed for three scenarios: two cases using a once through fuel cycle with only thermal reactors; and a plutonium recycle scenario based on thermal reactors and a break-even fast reactor with a breeding ratio of 1.0. Cross-checks indicated mostly similar trends among analytical tools used in the project. The codes showed consistent results related to the calculation of indicators in the area of fresh and discharged fuel flows and waste flows. The accuracy of the calculation supports reliable assessment of trends in the consumption of uranium and the accumulation of discharged fuel, fissile material and main components of radioactive waste for the selected scenarios. However, in the case of plutonium multi-recycle scenarios, different results may be obtained according to how the codes approximate the isotopic vectors of the available plutonium.

In cooperation with IAEA Member States, INPRO has also developed a methodology to assess how to achieve requirements for sustainability [1.5]. Consistent with the United Nations concept for sustainable development [1.10, 1.11], the INPRO Methodology is an holistic approach to assess the sustainability of innovative nuclear systems across seven areas:

(i) Economics;
(ii) Infrastructure;
(iii) Waste management;
(iv) Proliferation resistance;
(v) Physical protection;
(vi) The environment;
(vii) The safety of nuclear installations.

For each of these areas, a hierarchical set of Basic Principles, User Requirements and Criteria forms the basis for a sustainability assessment. The INPRO Methodology defines 14 Basic Principles, 52 User Requirements and 125 Criteria with Indicators and Acceptance Limits; all of which need to be met to ensure that an NES is sustainable.

Whereas the INPRO Methodology was designed as a tool for assessing the capabilities of a national NES to meet the requirements of sustainability, the GAINS framework is aimed at analysis and comparing options and possible scenarios at national, regional and global levels. Accordingly, the GAINS framework relates to INPRO Methodology primarily through the concept of key indicators introduced in INPRO Methodology reports [1.4, 1.5].

1.2. OBJECTIVE

The objective of this publication is to provide detailed guidance on how to build mathematical models representing complex NESs within the framework of MESSAGE. The specific objective is to facilitate the application of MESSAGE for modelling specific technical and economic features of NESs, including national or collaborative solutions based on a once through fuel cycle and a closed fuel cycle for thermal and fast reactors.

The IAEA Planning and Economic Studies Section and INPRO have jointly developed this User's Guide and used it in training provided to Member States — including joint training on the use of MESSAGE for evaluating different NES options towards sustainability within a framework of energy system analysis and planning. The experience of, and feedback from, the training has indicated a need to develop a guide for NES modelling with MESSAGE. This publication includes guidance on calculating mathematical mass flow, preparing an input dataset for different facilities, modelling special aspects of NESs with MESSAGE and assessing MESSAGE outputs, including economic results. It includes three demonstration cases:

(1) An NES based on thermal reactors with an open fuel cycle;
(2) An NES based on thermal reactors with reprocessing to feed plutonium as mixed oxide (MOX) fuel;
(3) An NES based on thermal and fast reactors with a fully closed fuel cycle.

Ultimately, users can modify the NES models according to the specific nuclear fuel cycle modelling approach.

1.3. SCOPE

This User's Guide is intended for experts who have basic knowledge of MESSAGE and an adequate understanding of NESs and their associated technologies, and who are interested in using MESSAGE for modelling an entire energy system with a full range of technical details in order to explore options for long term strategies for nuclear energy development in a country or region. Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

1.4. STRUCTURE

Section 2 describes the modelling of an NES based on thermal reactors with a once through fuel cycle. The reactors and fuels to be considered are heavy water reactors (HWRs) using natural uranium fuel, light water reactors (LWRs) using uranium oxide (UOX) fuel, and advanced light water reactors (ALWRs) using UOX fuel. Section 3 describes modelling an NES based on thermal reactors and spent fuel reprocessing to reuse plutonium as MOX fuel. The modelling considers two fuel types: UOX and MOX. Section 4 provides guidance on building a model of an NES based on thermal and fast reactors with a fully closed fuel cycle. The reactors and fuels considered are HWRs using natural uranium fuel, LWRs using UOX fuel, ALWRs using UOX fuel, and fast reactors using MOX fuel for the core and depleted uranium for the blankets.

Annexes I–III provide examples of reactor technologies and associated fuel cycle in MESSAGE format. A list of some of the most important abbreviations used in the figures and tables can be found at the end.

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2. DEMONSTRATION CASE 1: AN NES WITH AN OPEN FUEL CYCLE

Modelling an NES in MESSAGE is quite flexible, and users can decide which components they would like to include. In simple models, an NPP can be represented with inputs and outputs, together with its technical performance parameters and costs. An NPP requires nuclear fuel as the input to generate electricity as the main output and spent fuel discharged from the reactor as the secondary output (see Fig. 2.1).

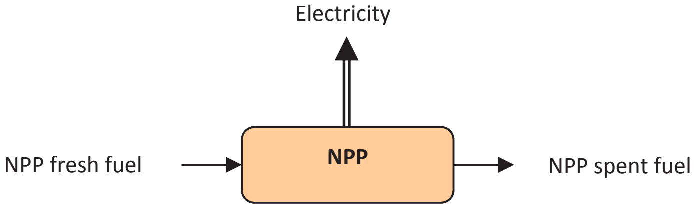


FIG. 2.1. Simplest NPP model.

Such NPP technology can be introduced in MESSAGE with the special energy forms ‘front end’ and ‘back end’, as shown in the network for a simple energy system (see Fig. 2.2). NPP technology consumes fresh fuel from the NPP fuel level of the back end energy form, and then produces secondary electricity and spent fuel.

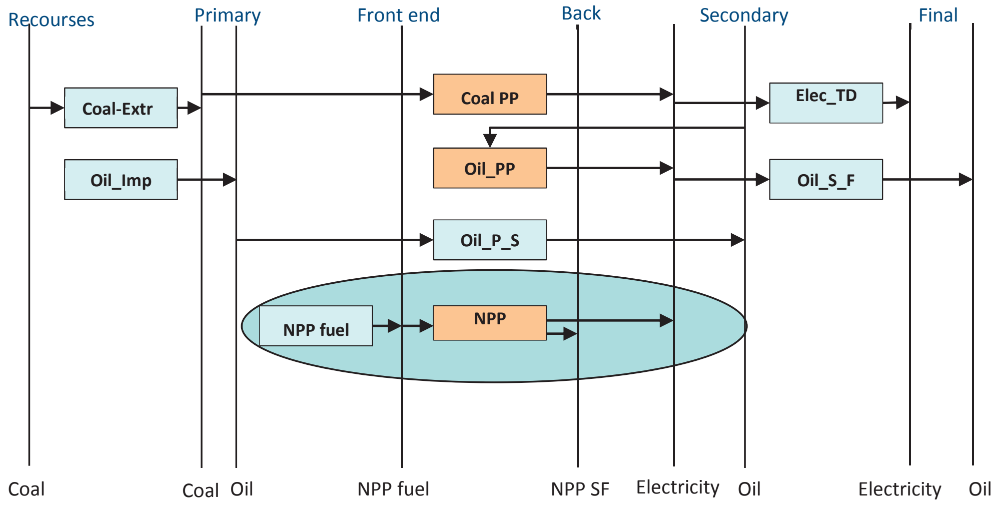


FIG. 2.2. Network for a simple energy system with an NPP.

However, the analysis of a nuclear fuel cycle requires more detailed modelling because it includes a set of processes to make nuclear fuel from natural uranium, generate electricity from the NPP and manage spent fuel discharged from the reactor. In a once through fuel cycle of an LWR, the front end of the nuclear fuel cycle includes mining and milling, conversion, enrichment and fuel fabrication. In the back end, spent fuel may be either finally disposed or stored temporarily for future use with reprocessing. Figure 2.3 shows the flow of front end and back end fuel cycle steps to model in MESSAGE an NES with an open fuel cycle.

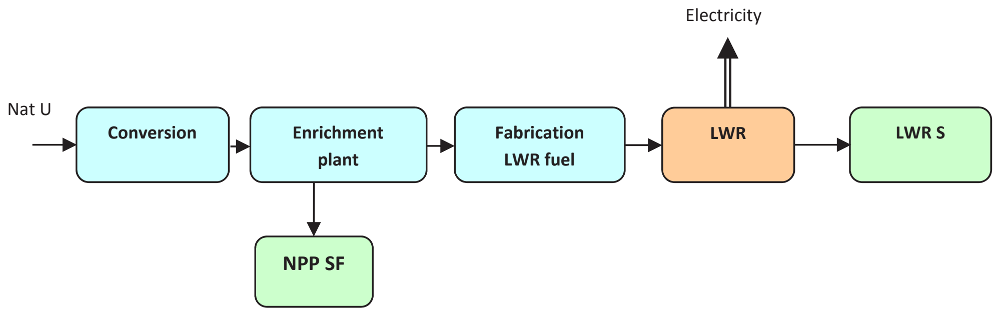


FIG. 2.3. *Once through fuel cycle of an LWR.*

2.1. ONCE THROUGH FUEL CYCLE MODEL WITH ONE UNIT OF AN LWR

The modelling steps within MESSAGE can be explained with the help of an example in which one unit of an LWR is considered. The first step is to prepare all the relevant input data for MESSAGE and to verify the mass balance of the once through fuel cycle of LWR material flow. The technical and economic parameters for each of the fuel cycle steps are required. Typical data for the LWR and its fuel cycle are given in Tables 2.1 and 2.2. All nuclear fuel cycle processes have some material losses. So for simplicity, all process losses are assumed to be zero.

The model simulates one unit of an LWR which is assumed to have 1000 MW(e) of installed capacity, with a capacity factor of 80%. The time period for the case is 2009–2160, with a constant demand of 800 MW·a. The interval up to 2100 is considered as the prognosis and is extended up to 2160 to take account of the boundary effects of linear modelling.

TABLE 2.1. TECHNICAL REACTOR AND FUEL CYCLE DATA FOR AN LWR

Item	Symbol	Unit	LWR
Nuclear capacity	NC	GW(e)	1
Load factor	Lf	n.a.[a]	0.8
Thermal efficiency	Eff	n.a.[a]	0.33
Discharge burnup	Bu	GW·d/t HM	45
Residence time	Tr	EFPD	1168
Enrichment of fresh fuel	Enr	n.a.[a]	0.04
Tails assay	Ta	n.a.[a]	0.003
Cooling time	Tcool	a	5

[a] n.a.: not applicable.

TABLE 2.2. ECONOMIC PARAMETERS OF AN LWR AND ITS FUEL CYCLE

Item	Unit	Reference value
Investment cost	US $/kW(e)	3000
Fixed O&M cost	US $/kW/a	55
Variable O&M cost	US $/kW·a	10
Lifetime	a	40
Construction time	a	5
Conversion	US $/kg HM	8
Enrichment	US $/kg HM	110
Fuel fabrication	US $/kg HM/a	275
Cooling storage	US $/kg HM/a	5
Interim storage	US $/kg HM	4
Natural uranium cost	US $/kg HM	40

All the fuel cycle steps shown in Fig. 2.2 need to be represented in the model. In general, the fuel cycle steps are considered as facilities with their capacity data, such as reactor technology. For simplicity, the conversion, fuel fabrication and enrichment steps in this example are considered as services that can be bought at a certain cost. However, they still need to be represented in MESSAGE with their respective technical parameters. Hence, the flow of nuclear material needs to be calculated to prepare the input dataset. Only the activity window should be filled out in this case.

2.1.1. Mathematical mass flow calculation for an open fuel cycle with one unit of an LWR

The average annual nuclear material flow for each step of the nuclear fuel cycle option (see Fig. 2.3) should be estimated based on the technical reactor and fuel cycle data (see Table 2.1.) The following are some well known analytical equations for mass flow calculations:

(a) Annual fresh fuel loading:

$$\mathrm{FF} = \frac{365 \times \mathrm{NC} \times \mathrm{Lf}}{\mathrm{Eff} \times \mathrm{Bu}} \tag{2.1}$$

(b) First loading (fuel in core):

$$\mathrm{FuelInCore} = \frac{\mathrm{FF} \times \mathrm{Tr}}{365 \times \mathrm{Lf}} \tag{2.2}$$

(c) Natural uranium consumption:

$$\mathrm{NatU} = \frac{\mathrm{FF} \times (\mathrm{Enr} - \mathrm{Ta})}{0.007114 - \mathrm{Ta}} \tag{2.3}$$

where 0.007 114 is the content of ^{235}U in natural uranium

(d) Conversion:

$$\mathrm{Cn} = \mathrm{NatU} \tag{2.4}$$

(e) Separative work unit:

$$\mathrm{SWU} = \mathrm{FF} \times \left(V(\mathrm{Enr}) + V(\mathrm{Ta}) \frac{\mathrm{Enr} - 0.007114}{0.007114 - \mathrm{Ta}} - V(0.007114) \frac{\mathrm{Enr} - \mathrm{Ta}}{0.007114 - \mathrm{Ta}} \right) \tag{2.5}$$

where

$$V(x) = (1 - 2x) \ln\left(\frac{1 - x}{x} \right)$$

(f) Depleted uranium production:

$$\mathrm{DepU} = \mathrm{FF} \times \frac{\mathrm{Enr} - 0.007114}{0.007114 - \mathrm{Ta}} \tag{2.6}$$

(g) Spent fuel discharged:

$$\mathrm{SFD} = \mathrm{FF} \tag{2.7}$$

The discharged fuel includes heavy metal and fission products. Using Eqs (2.1)–(2.7), the following can be calculated:

- Annual fresh fuel requirements;
- First fuel loading (fuel in core);
- Annual enrichment requirements;
- Annual depleted uranium amount;
- Annual conversion requirements;
- Annual natural uranium requirements;
- Annual spent fuel discharged amount.

The results are given in Table 2.3 and Fig. 2.4.

TABLE 2.3. ANALYTICAL MASS FLOW CALCULATIONS FOR AN OPEN FUEL CYCLE

Annual output parameters	Symbol	Equation	Unit	Analytical result
Fresh fuel	FF	(2.1)	t HM	19.7
Fuel in core	FuelInCore	(2.2)	t HM	78.7
Natural uranium	NatU	(2.3)	t HM	176.7
Conversion	Cn	(2.4)	t HM	176.7
Separative work unit	SWU	(2.5)	t SWU	104
Depleted uranium	DepU	(2.6)	t HM	157
Spent fuel discharged	SFD	(2.7)	t HM + t FP	19.7

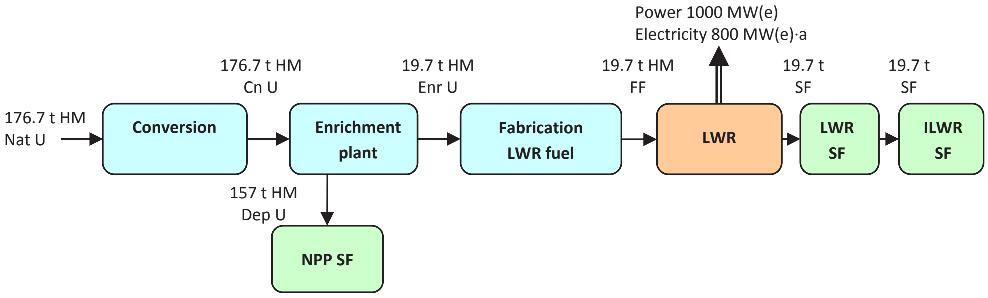


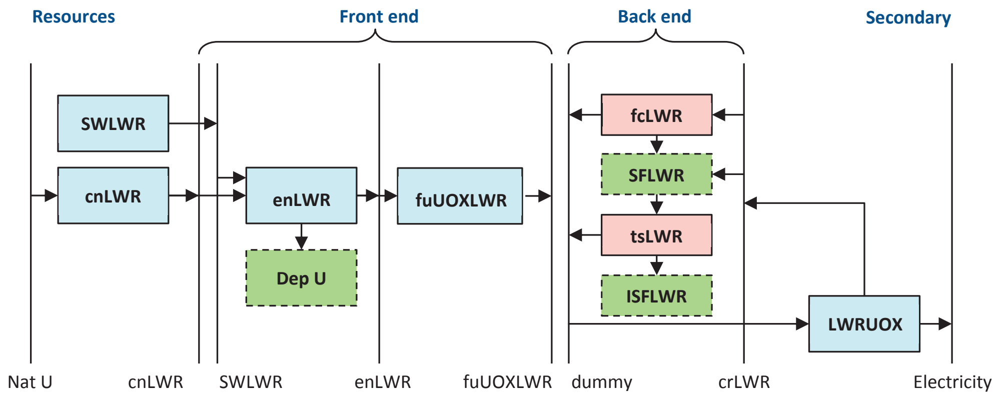
FIG. 2.4. Mass balance of a once through fuel cycle of an LWR.

2.1.2. MESSAGE modelling of an open fuel cycle with one unit of an LWR (Demo_Case_NFC11)

Table 2.4 provides the technology and types of storage, and Fig. 2.5 outlines the MESSAGE schematic energy chain of a once through fuel cycle option with an LWR.

TABLE 2.4. TECHNOLOGY AND STORAGE USED FOR MODELLING AN OPEN FUEL CYCLE

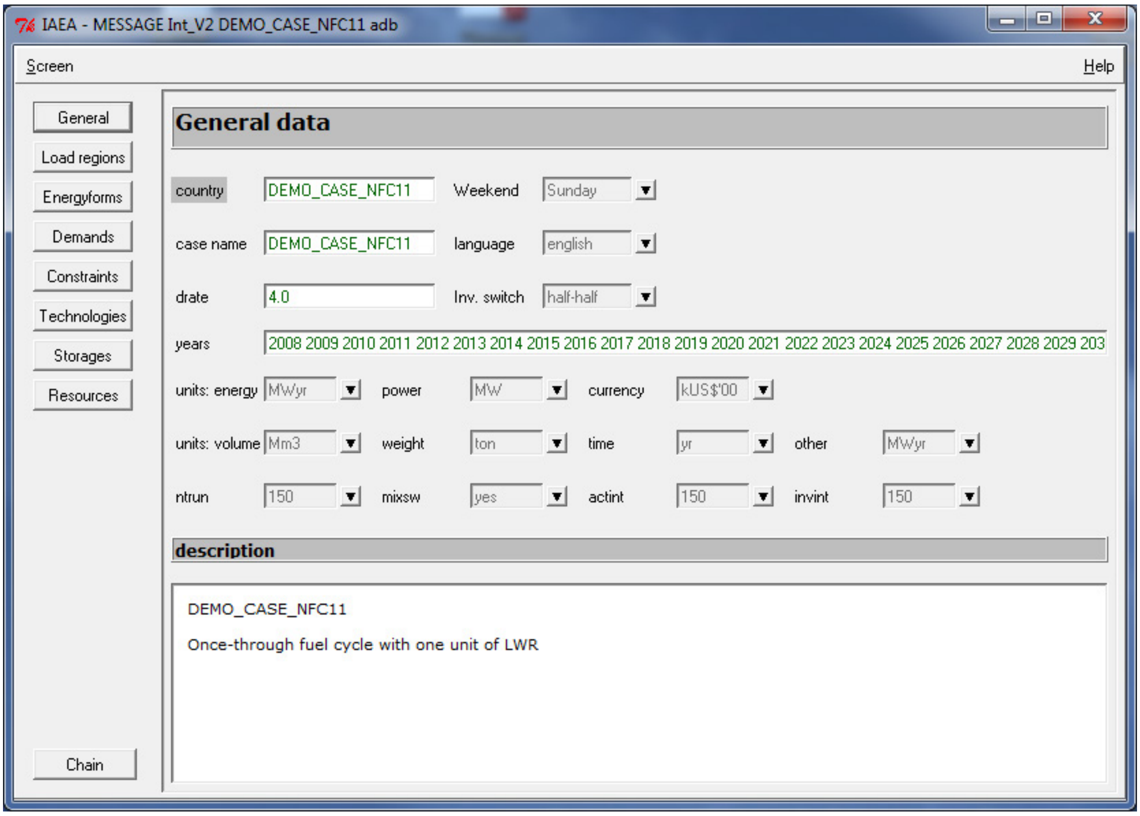
Technology and storage	Description
cnLWR	Conversion of uranium in the form of triuranium octoxide (U_3O_8) to uranium hexafluoride (UF_6)
enLWR	Enrichment of uranium
SWLWR	Auxiliary technology supplying separative work units
fuUOXLWR	UOX fuel fabrication
LWRUOX	LWR using UOX fuel
fcLWR	Auxiliary technology fcLWR puts discharged fuel to cooling storage SFLWR
tsLWR	Transport technology tsLWR moves spent fuel from cooling storage SFLWR to interim dry storage ISFLWR
dummy	Dummy back-stop technology
DepU	Depleted uranium storage
SFLWR	Cooling storage for LWR spent fuel
ISFLWR	Storage for LWR spent fuel after cooling



Note: See Table 2.4 for a description of the abbreviations.

FIG. 2.5. Schematic energy chain of a once through fuel cycle option with an LWR.

In this example in MESSAGE, the user first defines the modelling years and set the units correctly in the general data window (see Fig. 2.6). In this case, the time period is 2009–2160, and MW·a is used as a basic unit for energy, while MW for power and tonne for weight are used.



General data

country: DEMO_CASE_NFC11
Weekend: Sunday
case name: DEMO_CASE_NFC11
language: english
drate: 4.0
Inv. switch: half-half
years: 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 203
units: energy: MWyr
power: MW
currency: kUS$'00
units: volume: Mm3
weight: ton
time: yr
other: MWyr
ntrun: 150
mixsw: yes
actint: 150
invint: 150

description

DEMO_CASE_NFC11

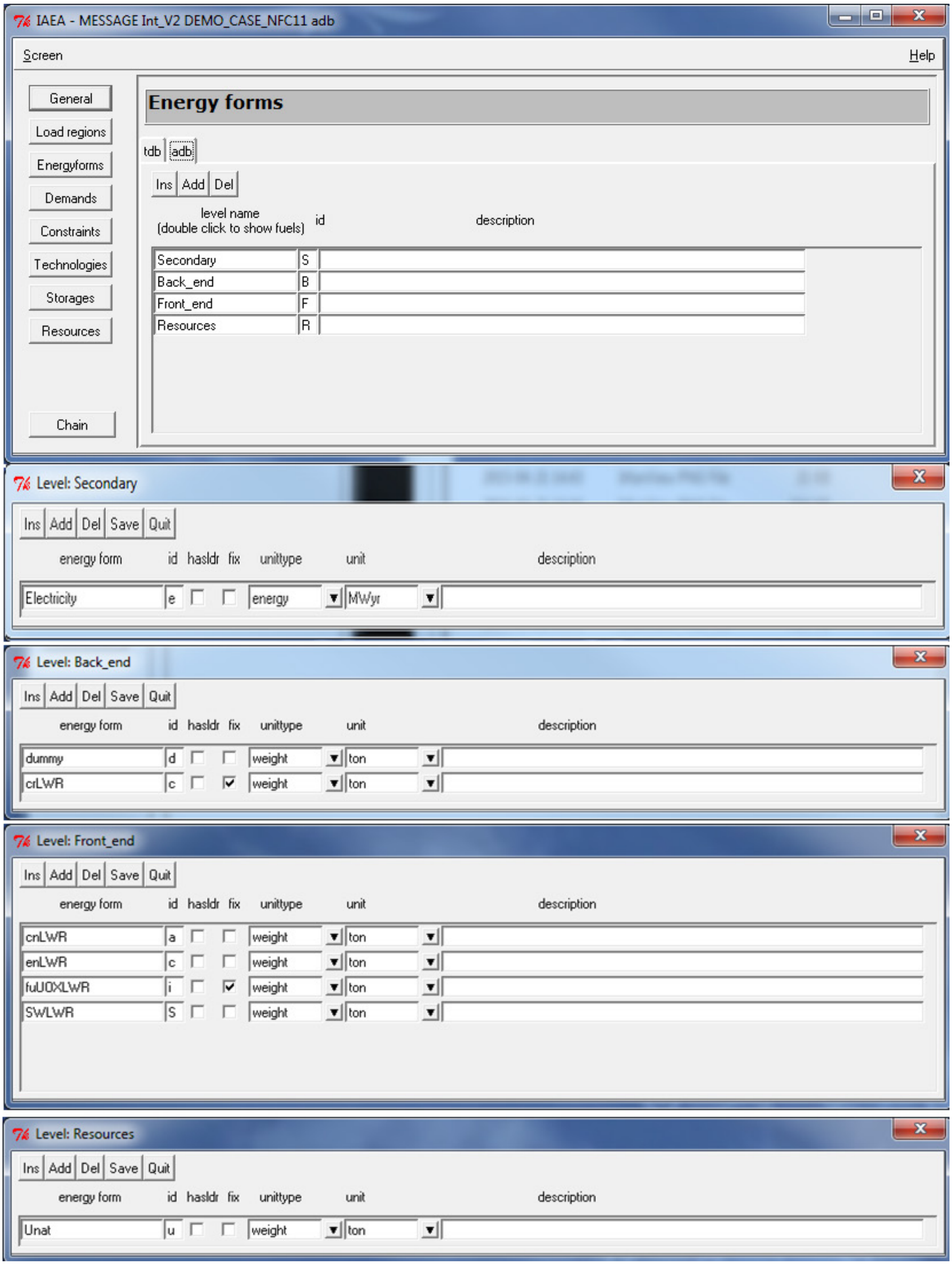
Once-through fuel cycle with one unit of LWR

FIG. 2.6. Defining the unit type in the general data window.

The user then defines all energy forms in different energy levels in a specific sequence (secondary, back end, front end and resource levels) in the energy forms window (see Fig. 2.7).

All units for the energy forms should be a unit of weight, except electricity at the secondary level. This can be done by double-clicking on the energy name box in the energy forms window and selecting the unit type and specific unit from the drop-down menu. It is also necessary to define units in the storages window. Thereby, it is necessary to note that the definition of units does not actually have an impact on the optimization result and mass flow calculation. The units are defined and entered only for the user to interpret the extracted results. While it is not required to include the units the model will take, the user should remember what the real units are. For example, the enrichment work unit in terms of weight unit for a separative work unit (SWU) means 1000 kg SWU.

Next, the user selects the tab labelled *Demands* to enter demand data. In this case, a constant demand of 800 MW·a should be entered as the electricity energy form at the secondary level. The user then goes to the resources window and selects Unat. On this form, the volume unit is defined and the cost of natural uranium at US $40/kg HM is entered. An empty value for volume means an unlimited quantity of this resource can be extracted (see Fig. 2.8).



level name (double click to show fuels)	id	description
Secondary	S	
Back_end	B	
Front_end	F	
Resources	R	

Level: Secondary

energy form	id	hasldr	fix	unittype	unit	description
Electricity	e	☐	☐	energy	MWyr	

Level: Back_end

energy form	id	hasldr	fix	unittype	unit	description
dummy	d	☐	☐	weight	ton	
crLWR	c	☐	☑	weight	ton	

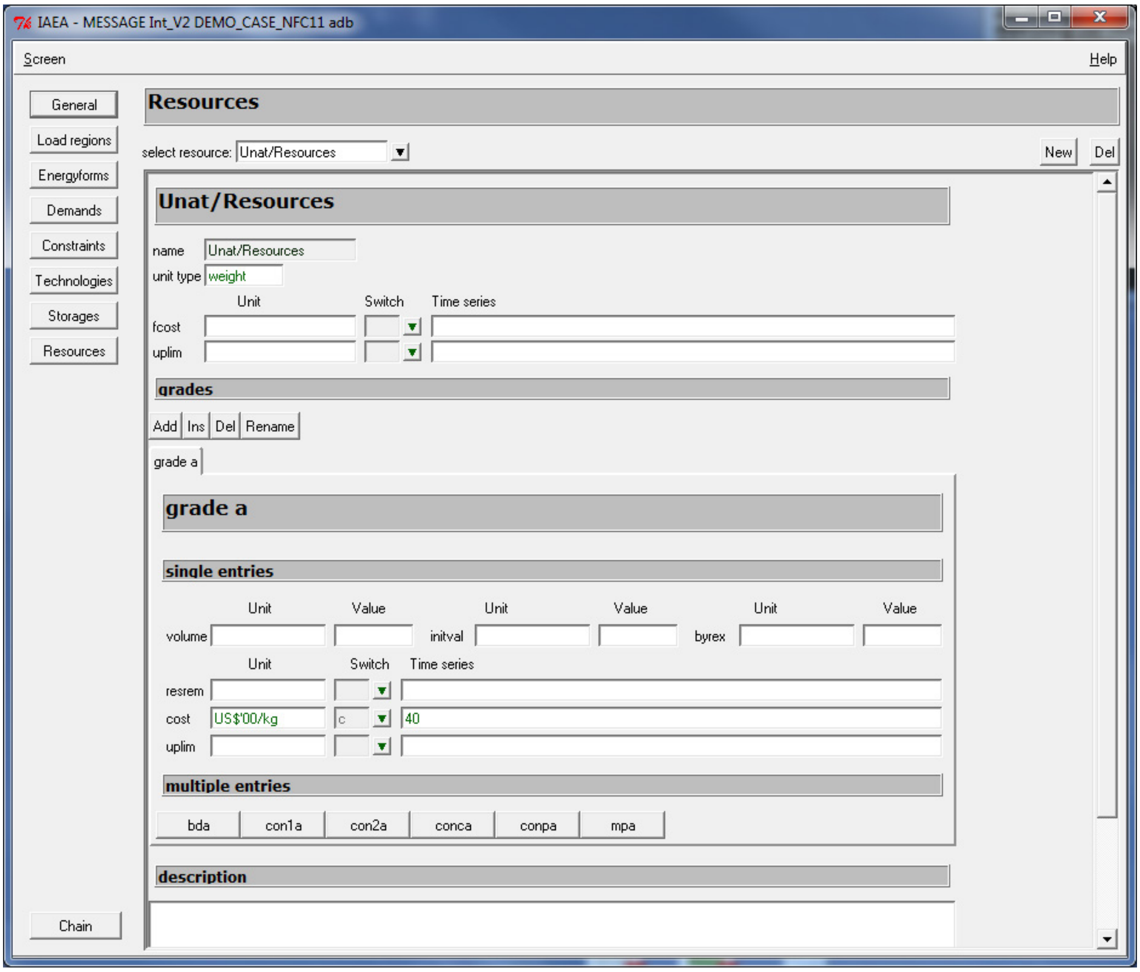
Level: Front_end

energy form	id	hasldr	fix	unittype	unit	description
cnLWR	a	☐	☐	weight	ton	
enLWR	c	☐	☐	weight	ton	
fuUOXLWR	i	☐	☑	weight	ton	
SWLWR	S	☐	☐	weight	ton	

Level: Resources

energy form	id	hasldr	fix	unittype	unit	description
Unat	u	☐	☐	weight	ton	

FIG. 2.7. Entering energy forms and unit type in the energy forms window.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC11 adb

Resources

select resource: Unat/Resources

Unat/Resources

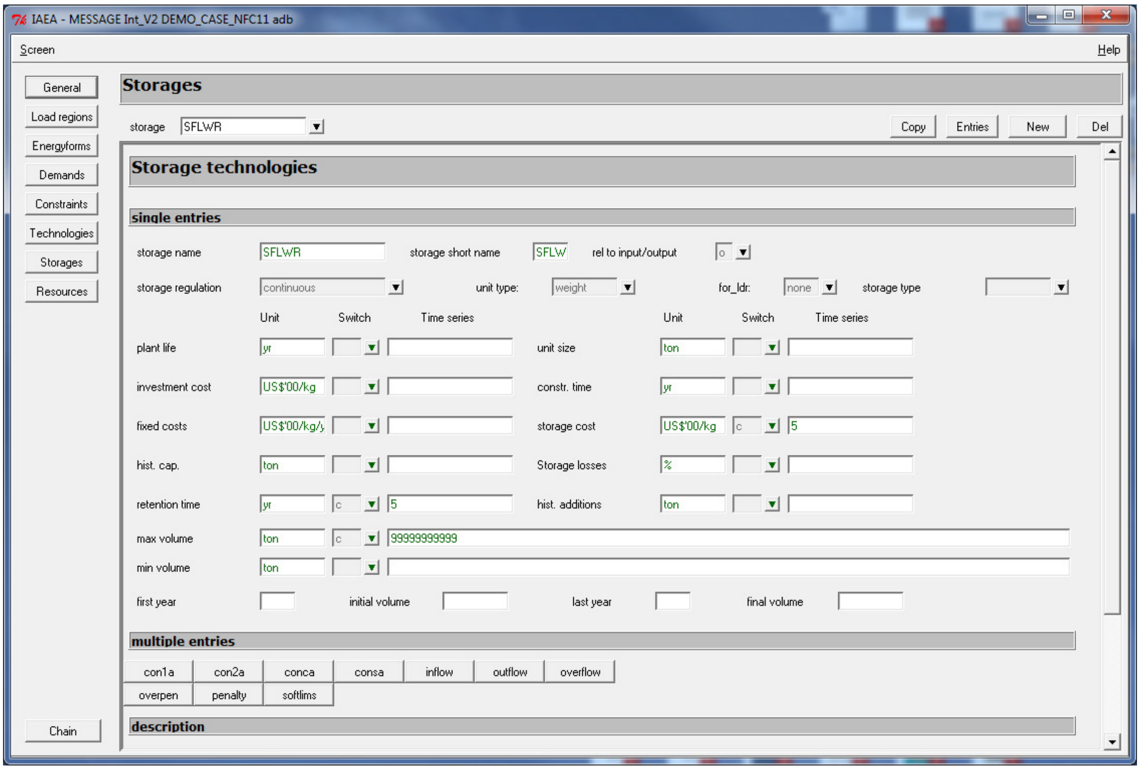
name: Unat/Resources
unit type: weight

grade a

cost: Unit US$'00/kg; Switch c; Time series 40

FIG. 2.8. *Resources window.*

In the next step, depleted uranium storage, cooling LWR storage and interim LWR storage should be modelled. The storages window can be opened by selecting the tab labelled *Storages*. As shown in Fig. 2.9, discharged fuel is stored at the reactor cooling pool SFLWR. Spent fuel is stored there for five years to remove the decay heat, and then it is moved to storage ISFLWR. Cooling time is modelled by the retention time input parameter in the corresponding data field. In the storages window, the unit type should be selected as weight. A large number should be put in the max volume data field, as MESSAGE requires the upper limit for storage volume as a mandatory input. Storage costs are US $5/kg and US $4/kg for SFLWR and ISFLWR, respectively (see Figs 2.9 and 2.10).



Storages

storage: SFLWR

Storage technologies

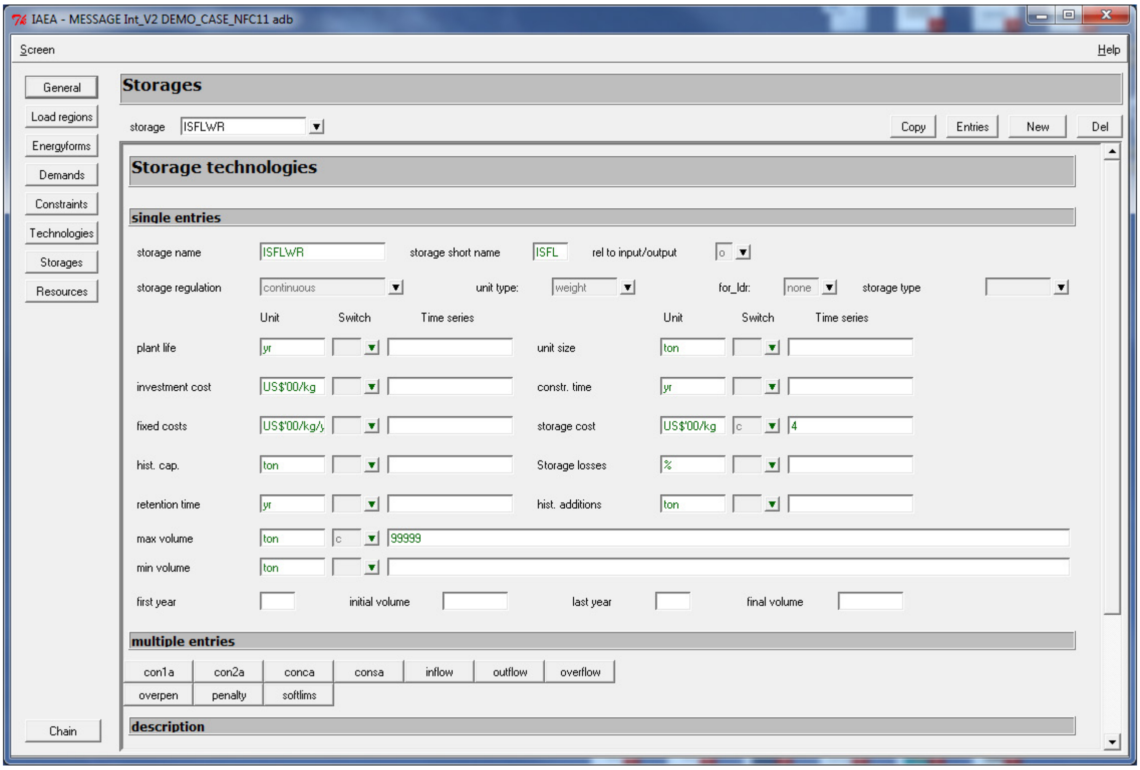
single entries

storage name: SFLWR
storage short name: SFLW
rel to input/output: o
storage regulation: continuous
unit type: weight
for_ldr: none
storage type:

	Unit	Switch	Time series		Unit	Switch	Time series
plant life	yr			unit size	ton		
investment cost	US$'00/kg			constr. time	yr		
fixed costs	US$'00/kg/y			storage cost	US$'00/kg	c	5
hist. cap.	ton			Storage losses	%		
retention time	yr	c	5	hist. additions	ton		
max volume	ton	c	99999999999				
min volume	ton						

first year: initial volume: last year: final volume:

FIG. 2.9. Modelling a cooling storage SFLWR.



Storages

storage: ISFLWR

Storage technologies

single entries

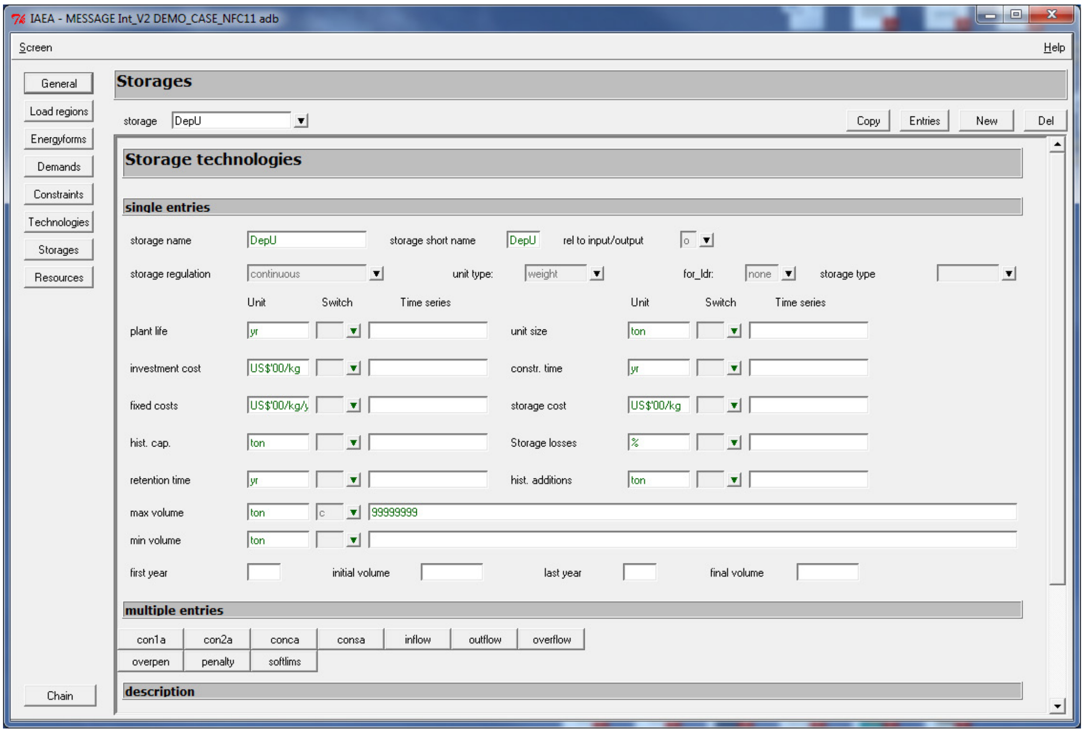
storage name: ISFLWR
storage short name: ISFL
rel to input/output: o
storage regulation: continuous
unit type: weight
for_ldr: none
storage type:

	Unit	Switch	Time series		Unit	Switch	Time series
plant life	yr			unit size	ton		
investment cost	US$'00/kg			constr. time	yr		
fixed costs	US$'00/kg/y			storage cost	US$'00/kg	c	4
hist. cap.	ton			Storage losses	%		
retention time	yr			hist. additions	ton		
max volume	ton	c	99999				
min volume	ton						

first year: initial volume: last year: final volume:

FIG. 2.10. Modelling a cooling storage ISFLWR.

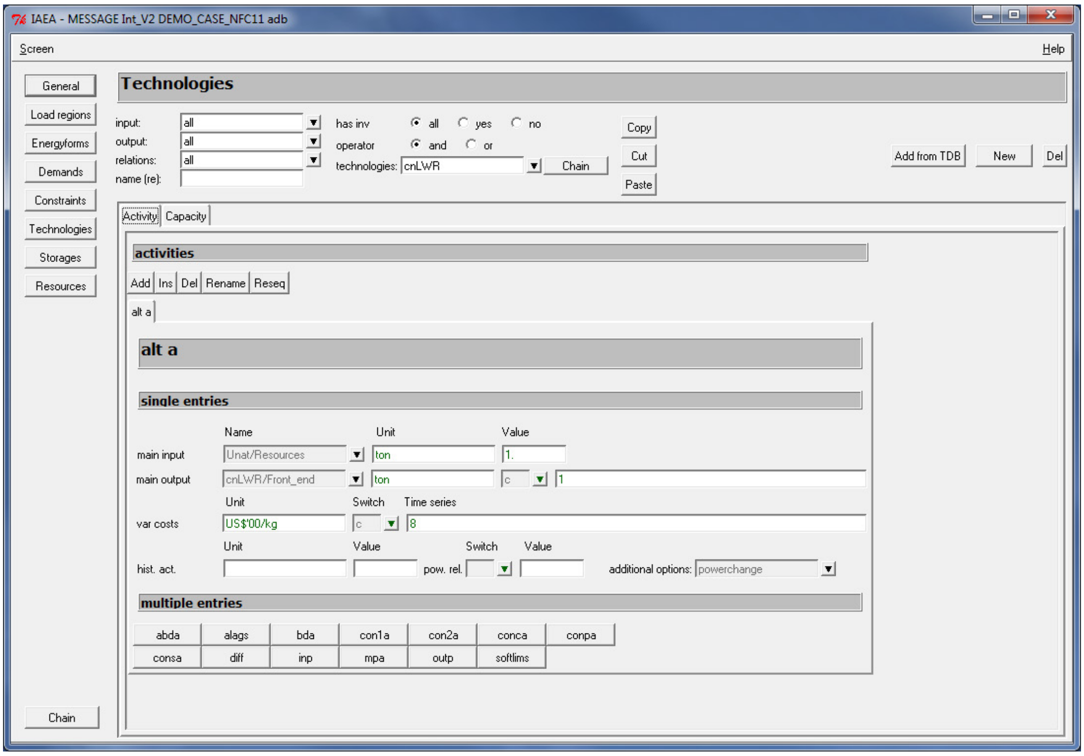
Depleted uranium from the enrichment process is stored at the deplete uranium storage DepU (see Fig. 2.11). The drop-down menu includes enrichment technology enLWR in relation with DepU storage.



storage: DepU

storage name: DepU
storage short name: DepU
rel to input/output: o
storage regulation: continuous
unit type: weight
for_ldr: none
storage type:
plant life: yr
unit size: ton
investment cost: US$'00/kg
constr. time: yr
fixed costs: US$'00/kg/y
storage cost: US$'00/kg
hist. cap.: ton
Storage losses: %
retention time: yr
hist. additions: ton
max volume: ton c 99999999
min volume: ton

FIG. 2.11. *Modelling a depleted uranium storage DepU.*



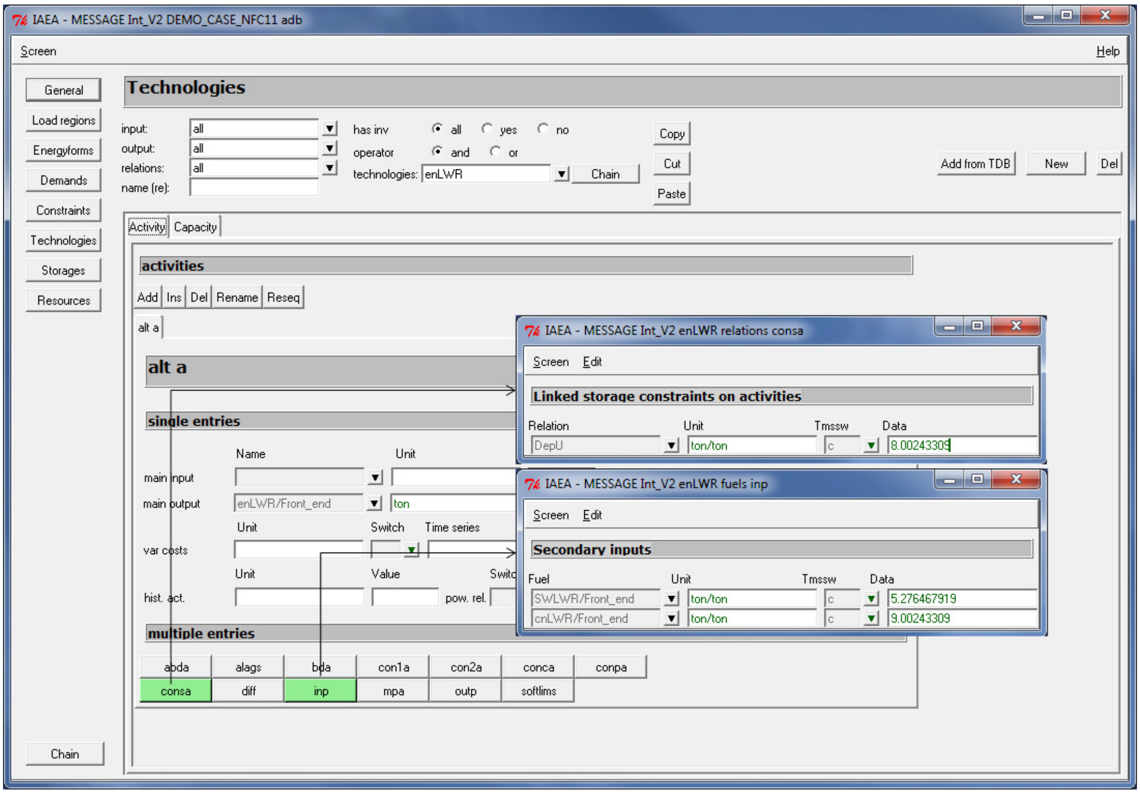
input: all
output: all
relations: all
name (re):
has inv: ● all ○ yes ○ no
operator: ● and ○ or
technologies: cnLWR

main input: Unat/Resources ton 1.
main output: cnLWR/Front_end ton c 1
var costs: US$'00/kg c 8
hist. act.:
pow. rel.:
additional options: powerchange

FIG. 2.12. *Modelling an LWR conversion technology.*

In the next step, the technologies should be modelled in MESSAGE. Conversion, enrichment, fuel fabrication and the LWR are defined in the technologies window (see Fig. 2.12). Based on the equations in Section 2.1.1 for the conversion technology cnLWR, for obtaining one unit of uranium hexafluoride (UF_6) as an output, one unit of natural uranium as an input is needed: therefore, 176.7 t HM natural uranium is converted to 176.7 t HM of UF_6 (ignoring conversion losses). Hence, the main input and main output in the technologies window will be specified as 1. The cost of conversion for one unit of output is assumed to be US $8/kg, which is entered in the data field for variable costs.

Enrichment is modelled by two technologies: enLWR (see Fig. 2.13) and SWLWR (see Fig. 2.14); enLWR technology produces enriched uranium, while SWLWR technology provides the SWU needed for the enrichment process. For obtaining 19.7 t HM of enriched uranium at the 4% level (an annual reload for one unit of an LWR of 1000 MW capacity), the enrichment process needs an input of 176.6 t HM of UF_6 and 104 t SWU, leaving 157 t HM of depleted uranium at the 0.3% level (see Table 2.3). Thus, one unit of enriched uranium requires around 9.0 units (= 176.6/19.7) of UF^6 and 5.3 units (= 104/19.7) of SWU, leaving 8.0 units (= 157/19.7) of depleted uranium.



input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: enLWR

alt a

single entries

	Name	Unit
main input		
main output	enLWR/Front_end	ton

	Unit	Switch	Time series
var costs			

	Unit	Value	pow. rel.
hist. act.			

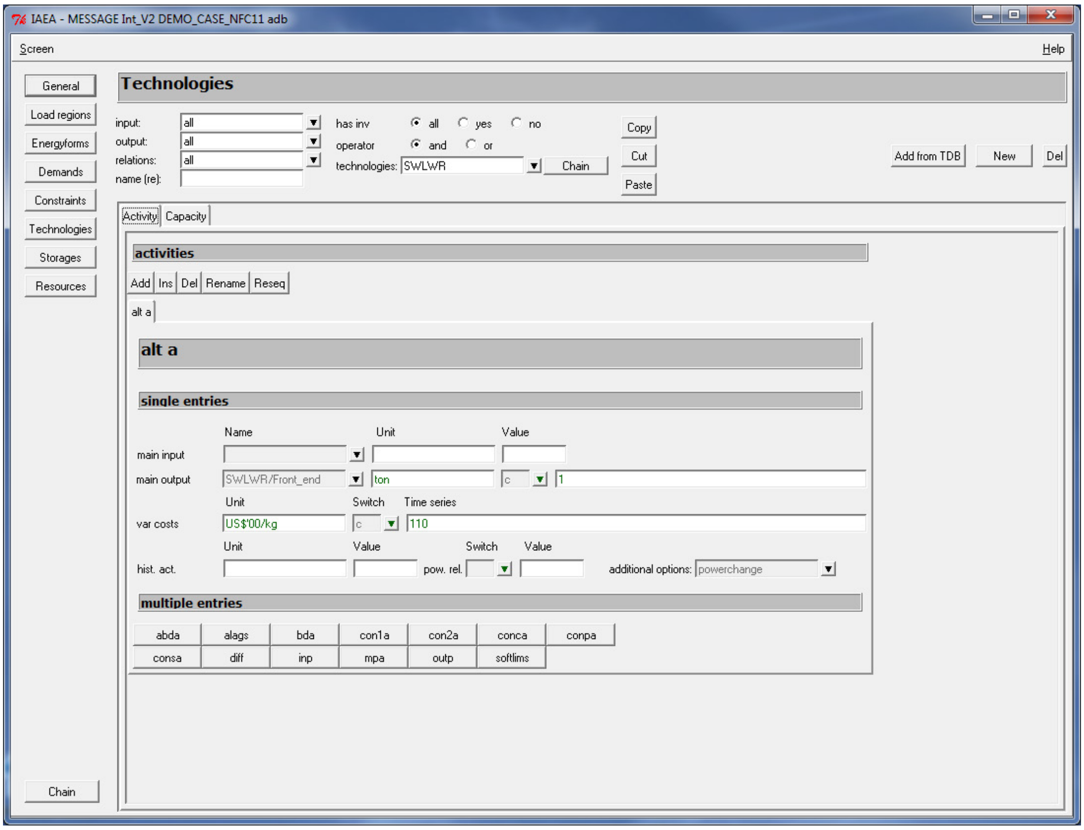
Linked storage constraints on activities

Relation	Unit	Tmssw	Data
DepU	ton/ton	c	8.00243309

Secondary inputs

Fuel	Unit	Tmssw	Data
SWLWR/Front_end	ton/ton	c	5.276467919
cnLWR/Front_end	ton/ton	c	9.00243309

FIG. 2.13. *Modelling an LWR enrichment technology.*


IAEA - MESSAGE Int_V2 DEMO_CASE_NFC11 adb

Technologies

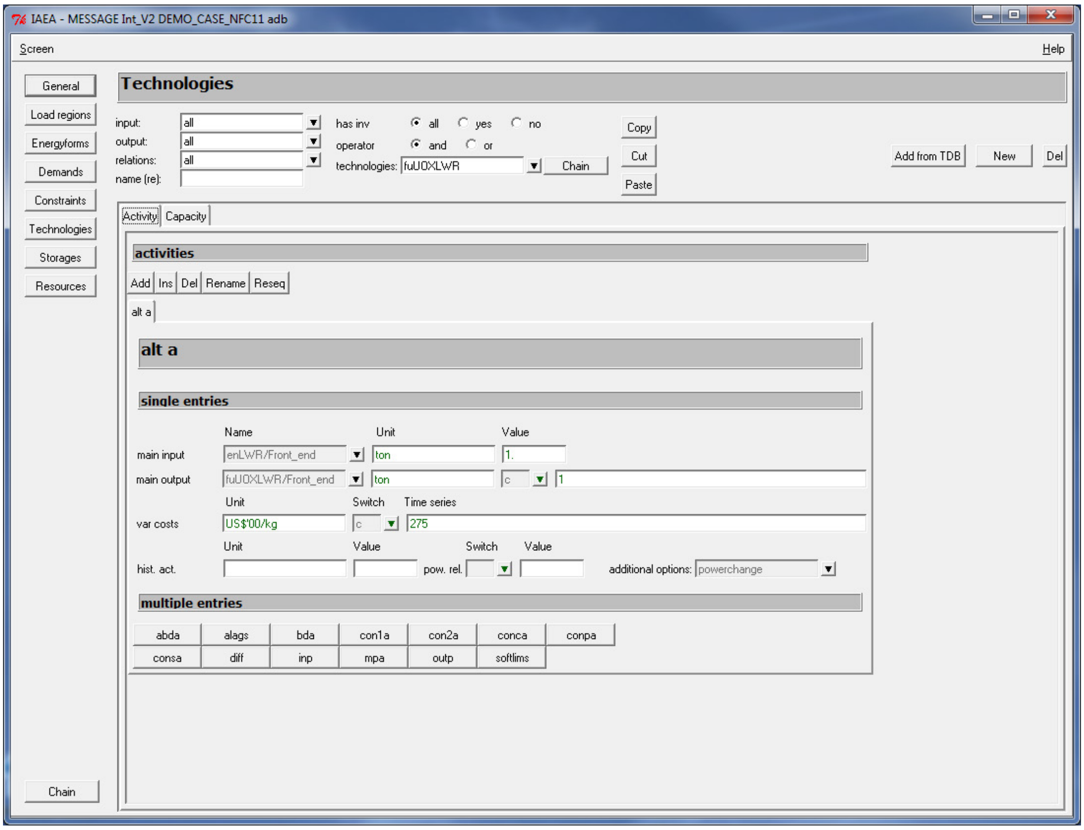
input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: SWLWR

alt a

single entries

main input: Name — ; Unit — ; Value —
main output: Name SWLWR/Front_end; Unit ton; c; 1
var costs: Unit US$'00/kg; Switch c; Time series 110
hist. act.: Unit — ; Value — ; pow. rel. — ; Value —
additional options: powerchange

FIG. 2.14. Modelling technology SWLWR.


IAEA - MESSAGE Int_V2 DEMO_CASE_NFC11 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: fuUOXLWR

alt a

single entries

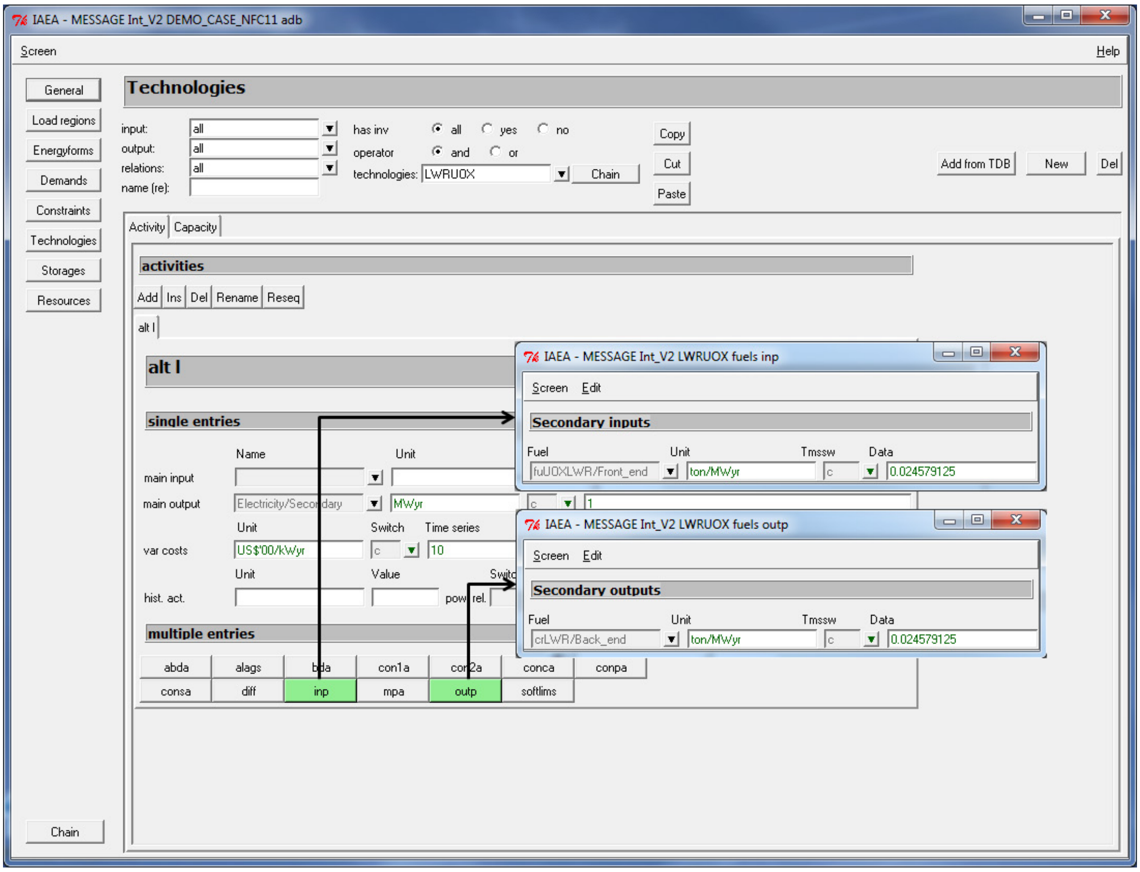
main input: Name enLWR/Front_end; Unit ton; Value 1.
main output: Name fuUOXLWR/Front_end; Unit ton; c; 1
var costs: Unit US$'00/kg; Switch c; Time series 275
hist. act.: Unit — ; Value — ; pow. rel. — ; Value —
additional options: powerchange

FIG. 2.15. Modelling the LWR fuel fabrication technology.

Figure 2.15 shows the technologies window for the fuel fabrication technology fuUOXLWR. This technology produces UOX fuel for loading into the reactor. One unit of fresh fuel needs one unit of enriched uranium. The amount of material thus remains the same: that is, 19.7 t HM of enriched uranium provides 19.7 t HM of fresh fuel at the fuel fabrication stage.

The representation of reactor LWRUOX is more complicated. The activity and capacity windows should be filled (see Figs 2.16 and 2.17). The reactor burns 19.7 t HM of fuel annually to produce 800 MW·a of electricity, and discharges 19.7 t of spent fuel, which includes heavy metals and fission products. In this case, input is given in weight units, while the main output is given in energy units. Normally, the main input and main output have the same units and are connected by a conversional coefficient. This coefficient is used to calculate coefficients in objective functions and to take account of data for multiple entries.

As reactor technology requires nuclear fuel input to generate electricity as an output, fresh fuel is considered a secondary input for this technology for the simplicity and exact accounting of material. For entering the input data, 19.7 t HM of fresh fuel should be converted to the relative fraction of the unit amount of main output (800 MW·a) and as a result, a value 0.024 6 (= 19.7/800) will go into the data field for the secondary input of this technology (see Fig. 2.16). The spent nuclear fuel discharged from the reactor is given as the secondary output for this technology and the input data is once again a fraction of the unit amount of main output (0.024 6). It goes to the dummy form crLWR and then to the cooling storage SFLWR.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC11 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: LWRUOX

activities

alt I

single entries

main input: Name ; Unit
main output: Name Electricity/Secondary ; Unit MWyr ; c ; 1
var costs: Unit US$'00/kWyr ; Switch c ; Time series 10
hist. act.: Unit ; Value ; pow rel.

multiple entries

IAEA - MESSAGE Int_V2 LWRUOX fuels inp

Secondary inputs

Fuel	Unit	Tmssw	Data
fuUOXLWR/Front_end	ton/MWyr	c	0.024579125

IAEA - MESSAGE Int_V2 LWRUOX fuels outp

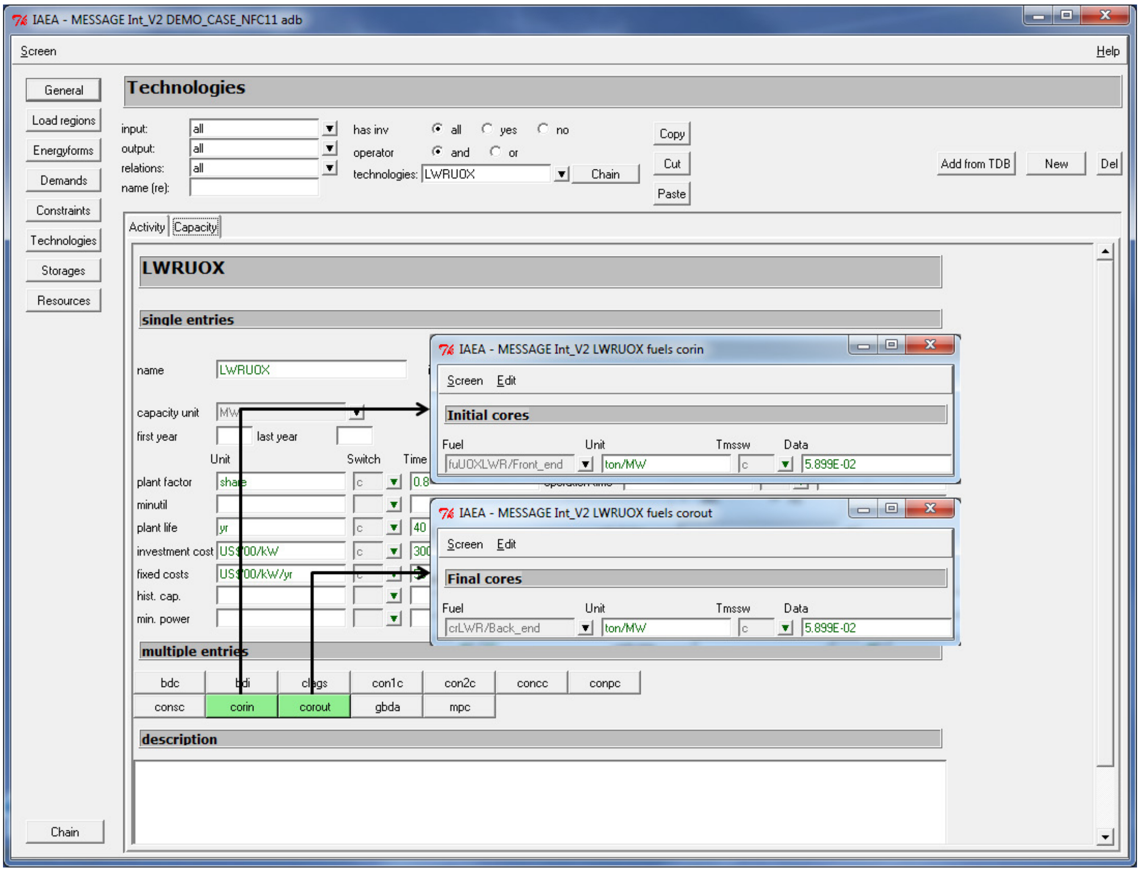
Secondary outputs

Fuel	Unit	Tmssw	Data
crLWR/Back_end	ton/MWyr	c	0.024579125

FIG. 2.16. *Modelling the LWR reactor technology in the activity window.*

The initial core loading and final core discharge data should be given as the fraction of the unit amount of the reactor's installed capacity. Two tabs labelled *corin* and *corout*, at the bottom part of the *Capacity* tab in the technologies window, are for the initial core loading and final core discharge, respectively (see Fig. 2.17). The installed capacity for LWRUOX is 1000 MW(e), the initial core loading is 78.7 t HM for UOX fuel and the annual reloading is 19.7 t HM for UOX fuel (see Table 2.3). It follows that the corresponding specific values in *corin* are 0.059 (= (78.7 − 19.7)/1000) for UOX fuel. The final core unloading (including fission products) is the same as the first core loading, so the specific value for *corout* data is also 0.059 for UOX spent fuel.

Figure 2.18 presents the auxiliary technology fcLWR. This technology puts discharged fuel from energy form crLWR to cooling storage SFLWR. While defining the energy form crLWR, the MESSAGE function 'fix' (see Fig. 2.7) should be used so that the spent fuel is delivered to the cooling storage (and not accumulated at the energy level). Transport technology tsLWR (see Fig. 2.19) transports spent fuel from the cooling storage SFLWR to the storage ISFLWR. Both of these technologies for transferring spent fuel have a dummy output because every technology in MESSAGE needs to have at least one output.



input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: LWRUOX

	Unit	Switch	Time
name	LWRUOX		
capacity unit	MW		
first year			
last year			
plant factor	share	c	0.8
minutil			
plant life	yr	c	40
investment cost	US$00/kW	c	300
fixed costs	US$00/kW/yr		
hist. cap.			
min. power			

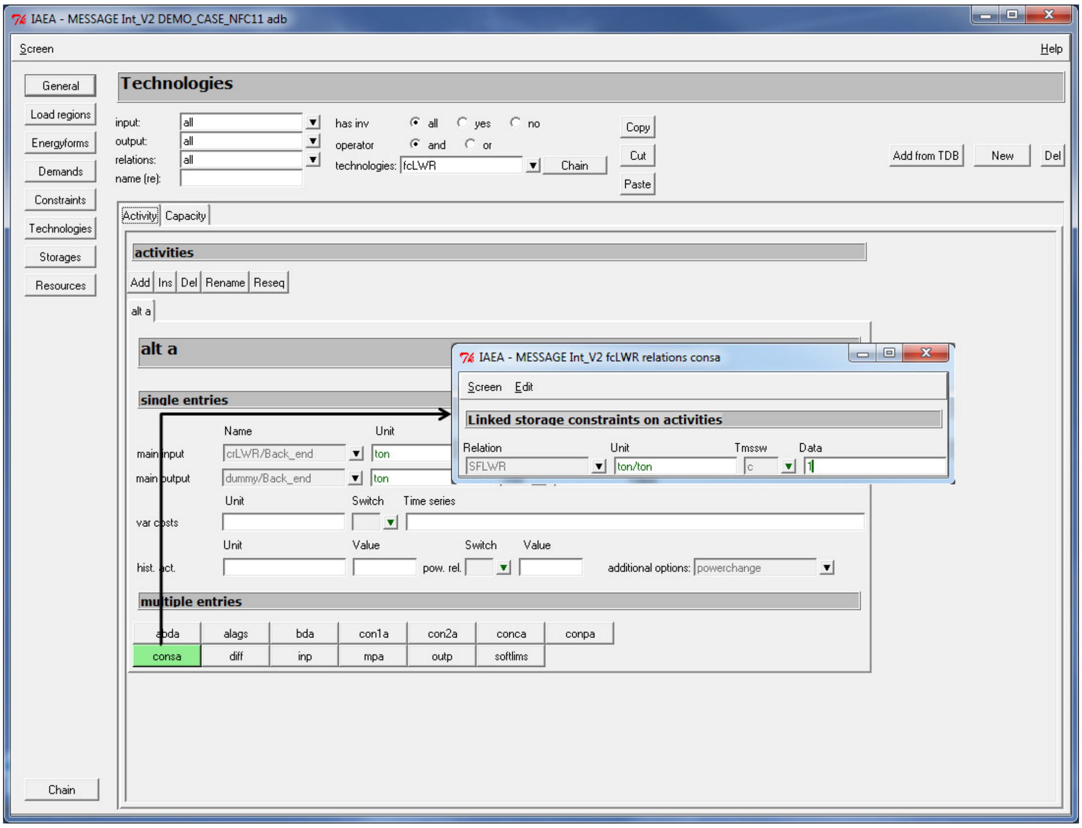
Initial cores

Fuel	Unit	Tmssw	Data
fuUOXLWR/Front_end	ton/MW	c	5.899E-02

Final cores

Fuel	Unit	Tmssw	Data
crLWR/Back_end	ton/MW	c	5.899E-02

FIG. 2.17. Modelling the LWR reactor technology in the capacity window.



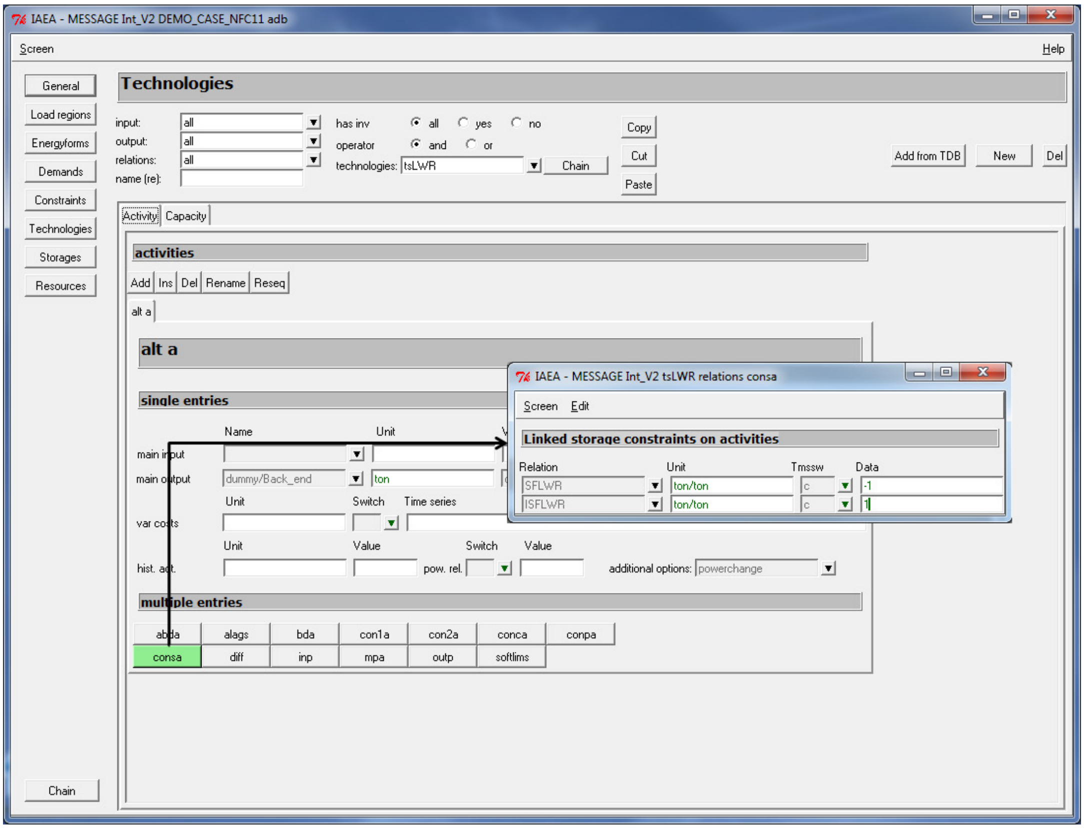
input: all
output: all
relations: all
name (re):
has inv: ● all ○ yes ○ no
operator: ● and ○ or
technologies: fcLWR
main input: crLWR/Back_end — ton
main output: dummy/Back_end — ton
pow. rel.
additional options: powerchange

IAEA - MESSAGE Int_V2 fcLWR relations consa

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
SFLWR	ton/ton	c	1

FIG. 2.18. Modelling the auxiliary technology fcLWR.



input: all
output: all
relations: all
name (re):
has inv: ● all ○ yes ○ no
operator: ● and ○ or
technologies: tsLWR
main input:
main output: dummy/Back_end — ton
pow. rel.
additional options: powerchange

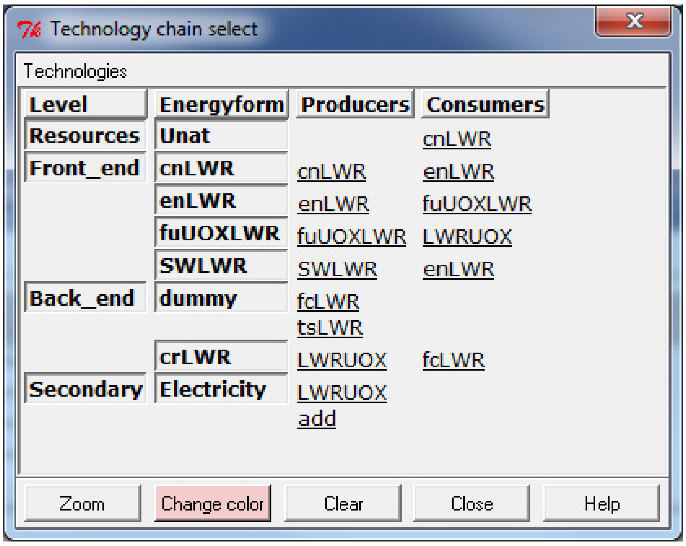
IAEA - MESSAGE Int_V2 tsLWR relations consa

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
SFLWR	ton/ton	c	-1
ISFLWR	ton/ton	c	1

FIG. 2.19. Modelling the transport technology tsLWR.

To view the main elements and building blocks of the model, the user can select the tab labelled *Chain*. This displays all the technologies in the system (see Fig. 2.20), and would help in checking whether the technologies are correctly connected in the system.



Level	Energyform	Producers	Consumers
Resources	Unat		cnLWR
Front_end	cnLWR	cnLWR	enLWR
	enLWR	enLWR	fuUOXLWR
	fuUOXLWR	fuUOXLWR	LWRUOX
	SWLWR	SWLWR	enLWR
Back_end	dummy	fcLWR tsLWR	
	crLWR	LWRUOX	fcLWR
Secondary	Electricity	LWRUOX add	

FIG. 2.20. Technology chain.

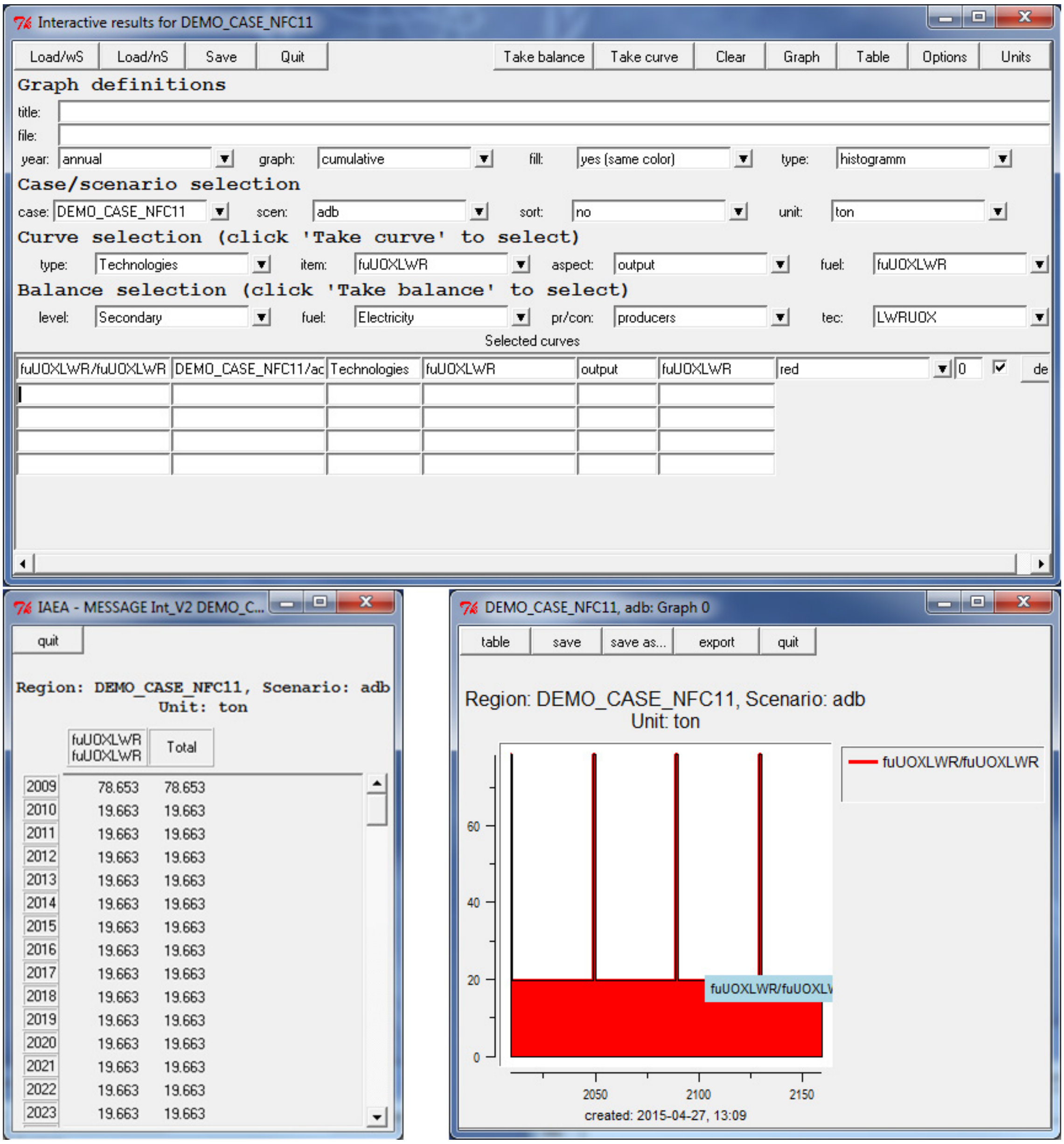
2.1.3. Mass flow MESSAGE outputs for an open fuel cycle with one unit of an LWR

After running MESSAGE Demo_Case_NFC1, the mass flow results can be displayed in the interactive mode of the Results menu and compared with analytical calculations (see Table 2.3). The selected and saved results are in Table 2.5.

TABLE 2.5. SELECTED MASS FLOW OUTPUTS FOR AN OPEN FUEL CYCLE

File name of results, selected and saved	Explanation
anNatU	Annual natural uranium requirements
SWU	Separative work unit requirements
FF	Fresh fuel requirements
anSF	Annual spent fuel discharged
anDepU	Annual depleted uranium production
DepU	Cumulative depleted uranium
SFLWR	Accumulation of spent fuel at cooling storage
ISFLWR	Accumulation of spent fuel at the storage after cooling

Fresh fuel requirements can be extracted by selecting the output of technology fuUOXLWR (see Fig. 2.21). The result in the table form is 19.7 t HM of annual fresh fuel requirements and 78.7 t HM in core (i.e. the same as the analytical result).



Interactive results for DEMO_CASE_NFC11

Graph definitions

title:

file:

year: annual graph: cumulative fill: yes (same color) type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11 scen: adb sort: no unit: ton

Curve selection (click 'Take curve' to select)

type: Technologies item: fuUOXLWR aspect: output fuel: fuUOXLWR

Balance selection (click 'Take balance' to select)

level: Secondary fuel: Electricity pr/con: producers tec: LWRUOX

Selected curves

fuUOXLWR/fuUOXLWR	DEMO_CASE_NFC11/ac	Technologies	fuUOXLWR	output	fuUOXLWR	red	0	☑	de

IAEA - MESSAGE Int_V2 DEMO_C...

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

	fuUOXLWR fuUOXLWR	Total
2009	78.653	78.653
2010	19.663	19.663
2011	19.663	19.663
2012	19.663	19.663
2013	19.663	19.663
2014	19.663	19.663
2015	19.663	19.663
2016	19.663	19.663
2017	19.663	19.663
2018	19.663	19.663
2019	19.663	19.663
2020	19.663	19.663
2021	19.663	19.663
2022	19.663	19.663
2023	19.663	19.663

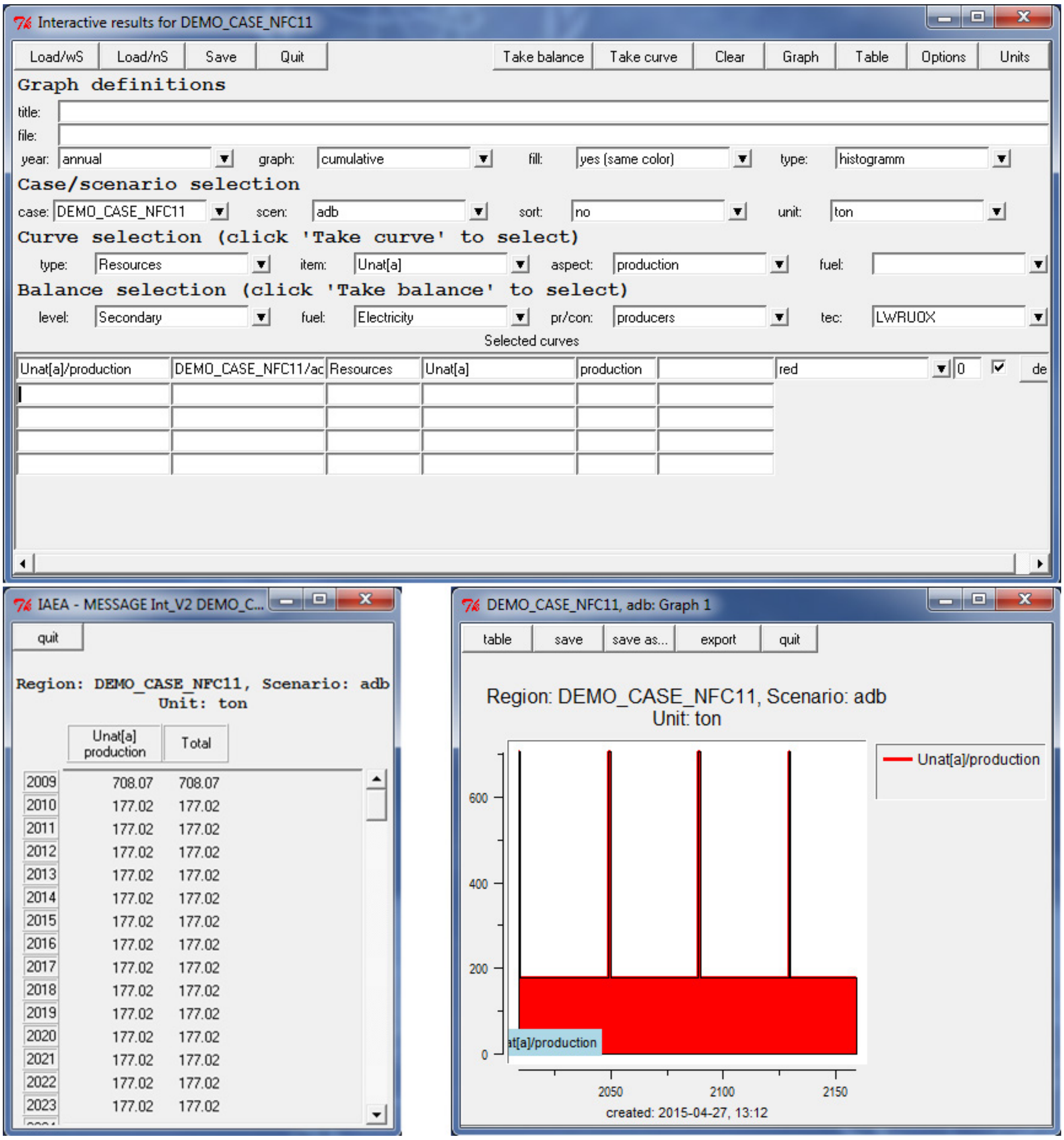
DEMO_CASE_NFC11, adb: Graph 0

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

created: 2015-04-27, 13:09

FIG. 2.21. Fresh fuel requirements.

The window for natural uranium requirements is shown in Fig. 2.22. The user should select type Resources and item Unat from the Curve selection. The natural uranium requirement (177 t HM) corresponds to the analytical results. Peaks in uranium consumption correspond to the first fuel loading.



Graph definitions

title:

file:

year: annual graph: cumulative fill: yes (same color) type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11 scen: adb sort: no unit: ton

Curve selection (click 'Take curve' to select)

type: Resources item: Unat[a] aspect: production fuel:

Balance selection (click 'Take balance' to select)

level: Secondary fuel: Electricity pr/con: producers tec: LWRUOX

Selected curves

Unat[a]/production | DEMO_CASE_NFC11/ac | Resources | Unat[a] | production | | red | 0 | ☑ | de

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

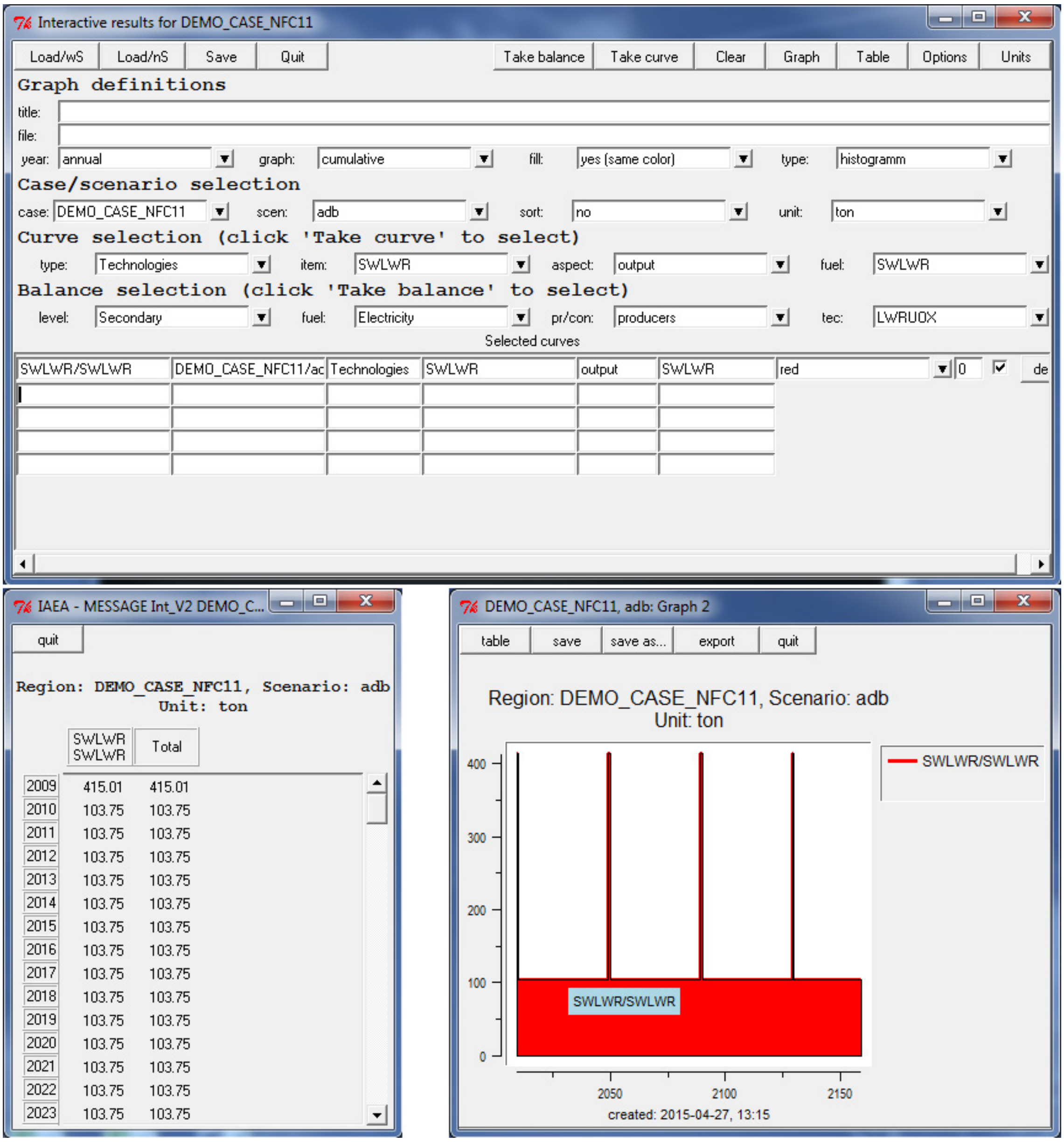
	Unat[a] production	Total
2009	708.07	708.07
2010	177.02	177.02
2011	177.02	177.02
2012	177.02	177.02
2013	177.02	177.02
2014	177.02	177.02
2015	177.02	177.02
2016	177.02	177.02
2017	177.02	177.02
2018	177.02	177.02
2019	177.02	177.02
2020	177.02	177.02
2021	177.02	177.02
2022	177.02	177.02
2023	177.02	177.02

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

created: 2015-04-27, 13:12

FIG. 2.22. Annual natural uranium requirements.

SWU requirements account for about 104 t SWU according to analytical calculations. This value can be viewed by selecting output of technology SWLWR (see Fig. 2.23).



Graph definitions

title:

file:

year: annual graph: cumulative fill: yes (same color) type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11 scen: adb sort: no unit: ton

Curve selection (click 'Take curve' to select)

type: Technologies item: SWLWR aspect: output fuel: SWLWR

Balance selection (click 'Take balance' to select)

level: Secondary fuel: Electricity pr/con: producers tec: LWRUOX

Selected curves

SWLWR/SWLWR	DEMO_CASE_NFC11/ac	Technologies	SWLWR	output	SWLWR	red	0	☑	de

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

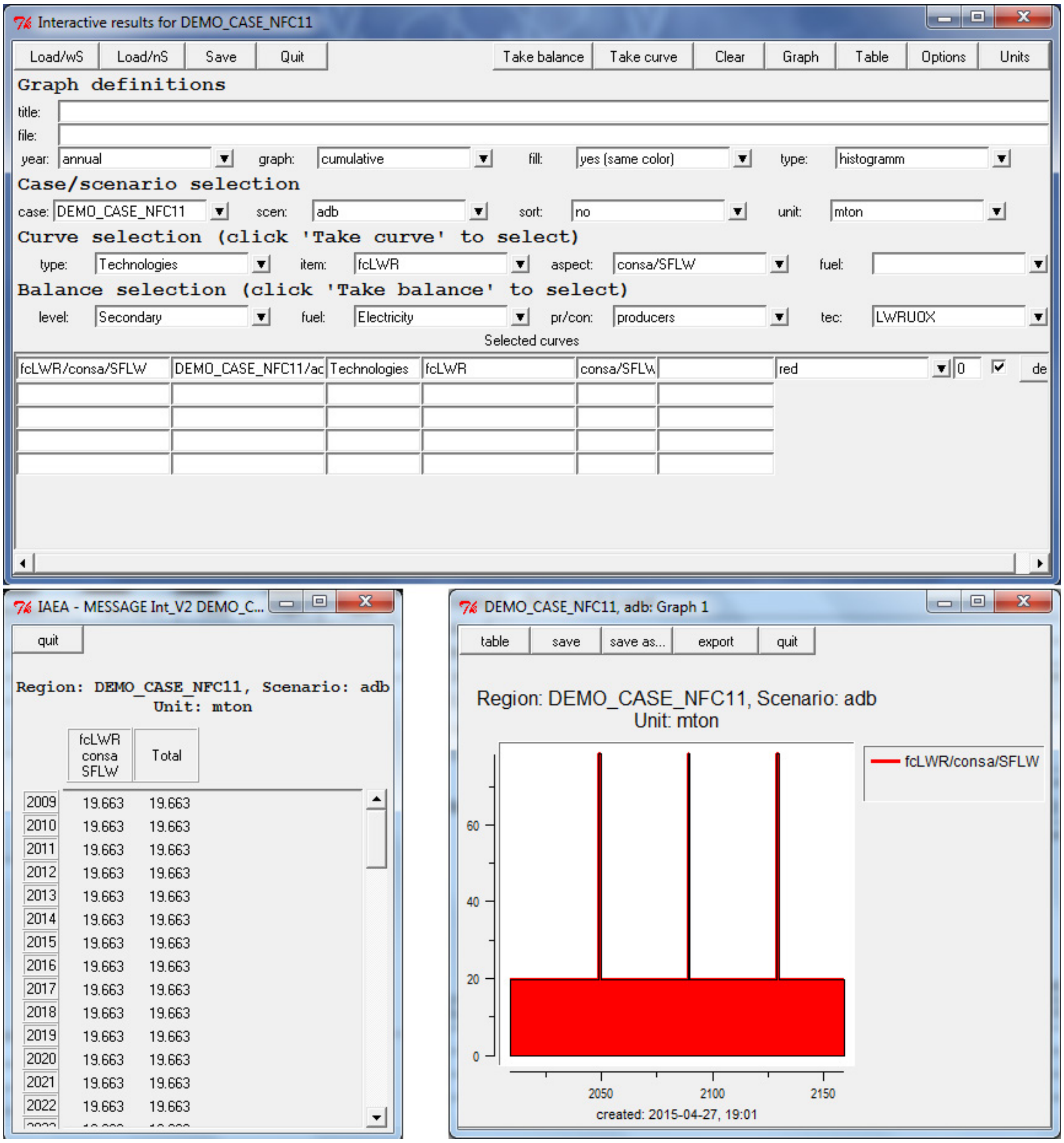
	SWLWR SWLWR	Total
2009	415.01	415.01
2010	103.75	103.75
2011	103.75	103.75
2012	103.75	103.75
2013	103.75	103.75
2014	103.75	103.75
2015	103.75	103.75
2016	103.75	103.75
2017	103.75	103.75
2018	103.75	103.75
2019	103.75	103.75
2020	103.75	103.75
2021	103.75	103.75
2022	103.75	103.75
2023	103.75	103.75

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

created: 2015-04-27, 13:15

FIG. 2.23. SWU requirements.

Spent fuel discharged (t HM + t FP) is equal to the fresh fuel requirements (19.7 t HM). This value can be extracted from consa aspect of technology fcLWR (see Fig. 2.24).



Graph definitions

title:

file:

year: annual | graph: cumulative | fill: yes (same color) | type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11 | scen: adb | sort: no | unit: mton

Curve selection (click 'Take curve' to select)

type: Technologies | item: fcLWR | aspect: consa/SFLW | fuel:

Balance selection (click 'Take balance' to select)

level: Secondary | fuel: Electricity | pr/con: producers | tec: LWRUOX

Selected curves

fcLWR/consa/SFLW | DEMO_CASE_NFC11/ac | Technologies | fcLWR | consa/SFLW | | red | 0 | ☑ | de

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: mton

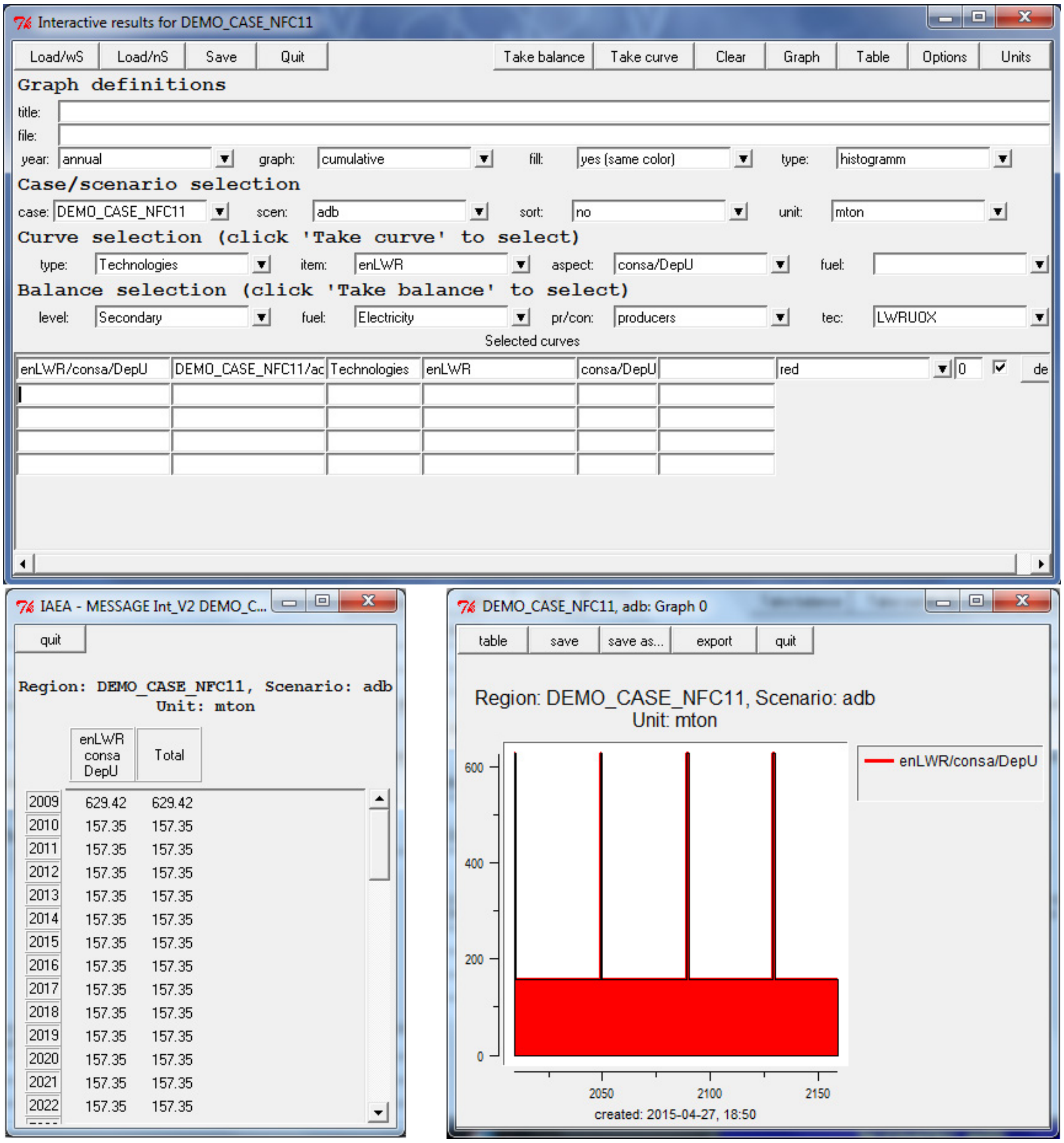
	fcLWR consa SFLW	Total
2009	19.663	19.663
2010	19.663	19.663
2011	19.663	19.663
2012	19.663	19.663
2013	19.663	19.663
2014	19.663	19.663
2015	19.663	19.663
2016	19.663	19.663
2017	19.663	19.663
2018	19.663	19.663
2019	19.663	19.663
2020	19.663	19.663
2021	19.663	19.663
2022	19.663	19.663

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: mton

created: 2015-04-27, 19:01

FIG. 2.24. *Annual spent fuel discharged.*

Annual depleted uranium production is given by the consa/DepU aspect of technology enLWR. The value is 157.4 t HM, which corresponds to the analytical calculations (see Fig. 2.25).



Interactive results for DEMO_CASE_NFC11

Graph definitions

title:
file:
year: annual
graph: cumulative
fill: yes (same color)
type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11
scen: adb
sort: no
unit: mton

Curve selection (click 'Take curve' to select)

type: Technologies
item: enLWR
aspect: consa/DepU
fuel:

Balance selection (click 'Take balance' to select)

level: Secondary
fuel: Electricity
pr/con: producers
tec: LWRUOX

Selected curves

enLWR/consa/DepU | DEMO_CASE_NFC11/ac | Technologies | enLWR | consa/DepU | | red | 0 | ☑ | de

IAEA - MESSAGE Int_V2 DEMO_C...

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: mton

	enLWR consa DepU	Total
2009	629.42	629.42
2010	157.35	157.35
2011	157.35	157.35
2012	157.35	157.35
2013	157.35	157.35
2014	157.35	157.35
2015	157.35	157.35
2016	157.35	157.35
2017	157.35	157.35
2018	157.35	157.35
2019	157.35	157.35
2020	157.35	157.35
2021	157.35	157.35
2022	157.35	157.35

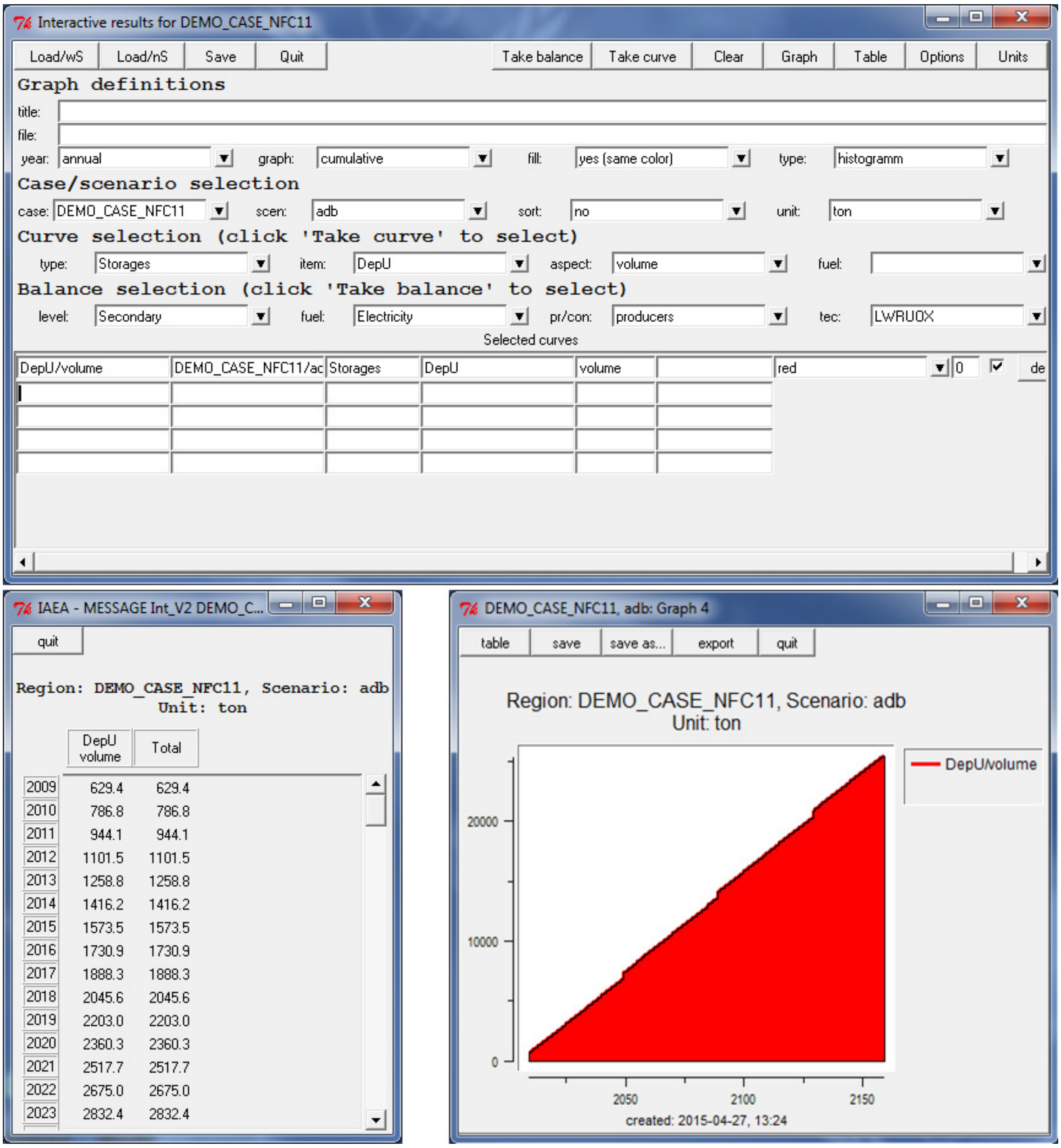
DEMO_CASE_NFC11, adb: Graph 0

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: mton

created: 2015-04-27, 18:50

FIG. 2.25. Annual depleted uranium production.

Depleted uranium accumulation can be extracted by selecting volume of storage DepU (see Fig. 2.26). The small steps in the figure are explained by the first fuel loading.



Graph definitions

title:

file:

year: annual
graph: cumulative
fill: yes (same color)
type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11
scen: adb
sort: no
unit: ton

Curve selection (click 'Take curve' to select)

type: Storages
item: DepU
aspect: volume
fuel:

Balance selection (click 'Take balance' to select)

level: Secondary
fuel: Electricity
pr/con: producers
tec: LWRUOX

Selected curves

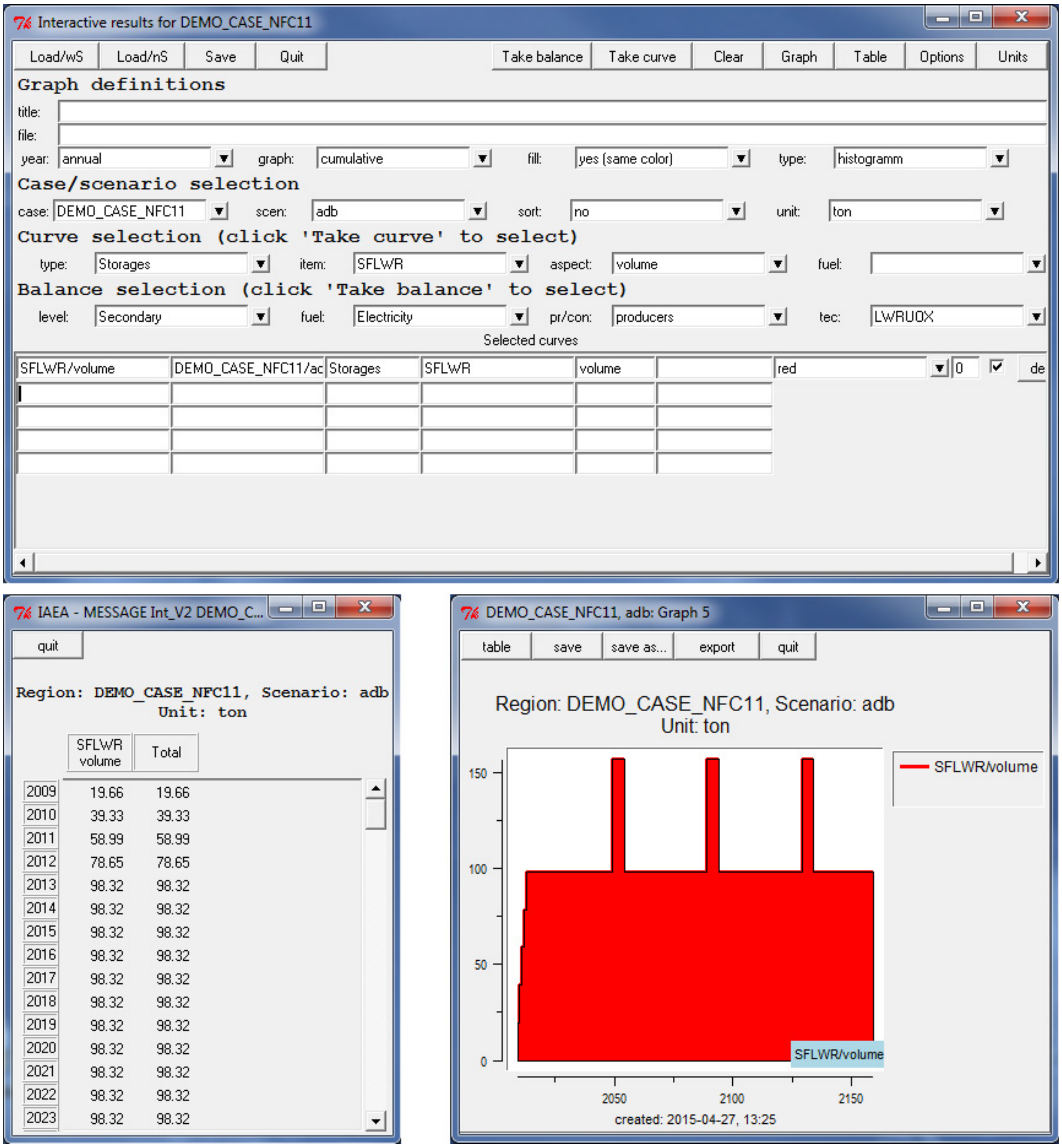
DepU/volume | DEMO_CASE_NFC11/ac | Storages | DepU | volume | | red | 0 | ☑ | de

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

	DepU volume	Total
2009	629.4	629.4
2010	786.8	786.8
2011	944.1	944.1
2012	1101.5	1101.5
2013	1258.8	1258.8
2014	1416.2	1416.2
2015	1573.5	1573.5
2016	1730.9	1730.9
2017	1888.3	1888.3
2018	2045.6	2045.6
2019	2203.0	2203.0
2020	2360.3	2360.3
2021	2517.7	2517.7
2022	2675.0	2675.0
2023	2832.4	2832.4

FIG. 2.26. Cumulative depleted uranium.

The accumulation of spent fuel at the cooling pool is extracted by selecting volume of storage SFLWR (see Fig. 2.27). Every year, 19.7 t of spent fuel is discharged to the cooling pool. After five years of cooling, the spent fuel needs to go to the interim storage, so fuel accumulation becomes constant. Peaks are a result of the final fuel unloading from the core.



Graph definitions

title:

file:

year: annual
graph: cumulative
fill: yes (same color)
type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11
scen: adb
sort: no
unit: ton

Curve selection (click 'Take curve' to select)

type: Storages
item: SFLWR
aspect: volume
fuel:

Balance selection (click 'Take balance' to select)

level: Secondary
fuel: Electricity
pr/con: producers
tec: LWRUOX

Selected curves

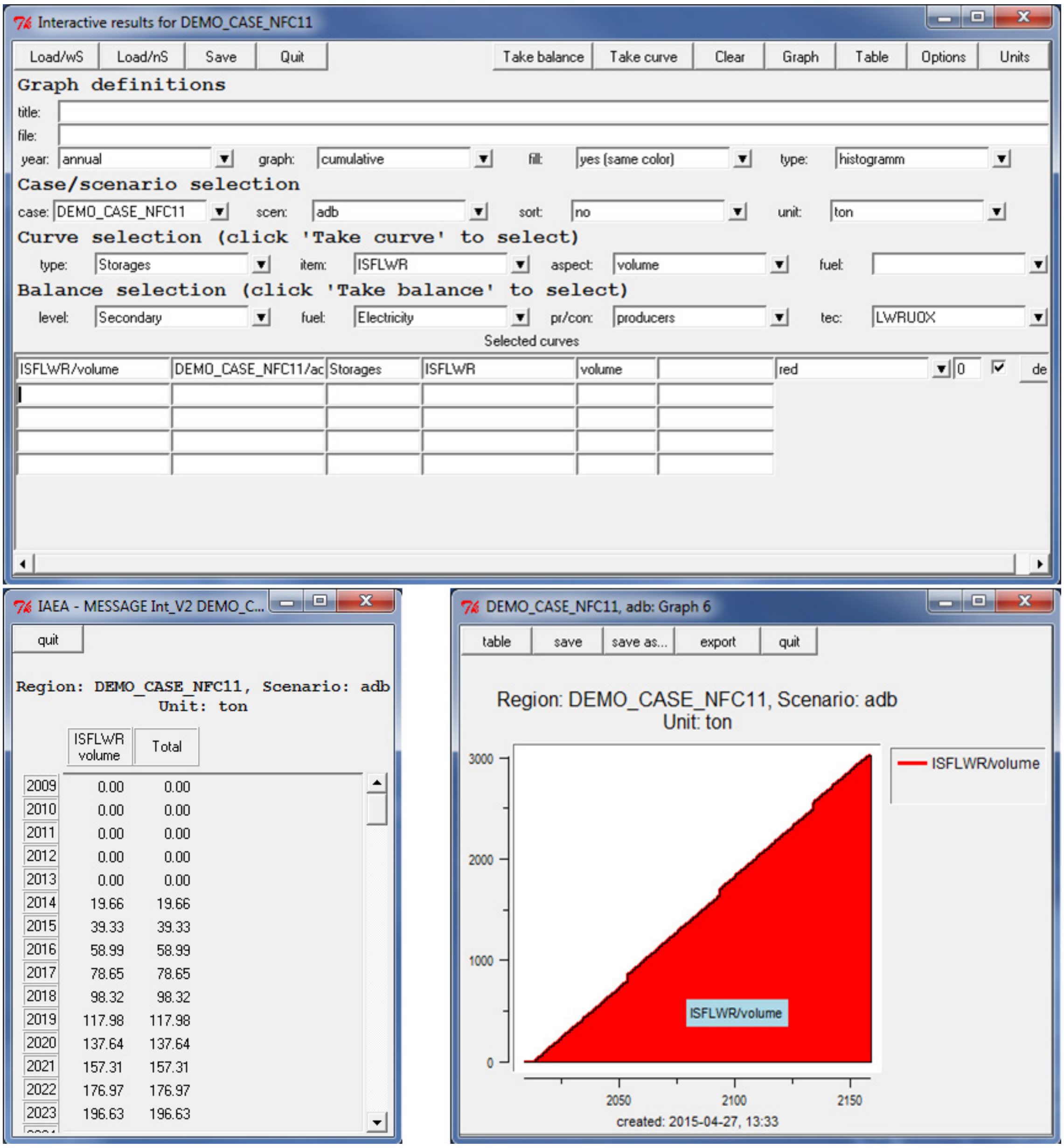
SFLWR/volume	DEMO_CASE_NFC11/ac	Storages	SFLWR	volume		red	0	☑	de

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

	SFLWR volume	Total
2009	19.66	19.66
2010	39.33	39.33
2011	58.99	58.99
2012	78.65	78.65
2013	98.32	98.32
2014	98.32	98.32
2015	98.32	98.32
2016	98.32	98.32
2017	98.32	98.32
2018	98.32	98.32
2019	98.32	98.32
2020	98.32	98.32
2021	98.32	98.32
2022	98.32	98.32
2023	98.32	98.32

FIG. 2.27. Accumulation of spent fuel at cooling pool.

The accumulation of spent fuel at interim storage starts after five years of cooling and then increases by 19.7 t of spent fuel each year (see Fig. 2.28).



Interactive results for DEMO_CASE_NFC11

Graph definitions

title:
file:
year: annual graph: cumulative fill: yes (same color) type: histogramm

Case/scenario selection

case: DEMO_CASE_NFC11 scen: adb sort: no unit: ton

Curve selection (click 'Take curve' to select)

type: Storages item: ISFLWR aspect: volume fuel:

Balance selection (click 'Take balance' to select)

level: Secondary fuel: Electricity pr/con: producers tec: LWRUOX

Selected curves

ISFLWR/volume | DEMO_CASE_NFC11/ac | Storages | ISFLWR | volume | | red | 0 | ☑ | de

IAEA - MESSAGE Int_V2 DEMO_C...

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

	ISFLWR volume	Total
2009	0.00	0.00
2010	0.00	0.00
2011	0.00	0.00
2012	0.00	0.00
2013	0.00	0.00
2014	19.66	19.66
2015	39.33	39.33
2016	58.99	58.99
2017	78.65	78.65
2018	98.32	98.32
2019	117.98	117.98
2020	137.64	137.64
2021	157.31	157.31
2022	176.97	176.97
2023	196.63	196.63

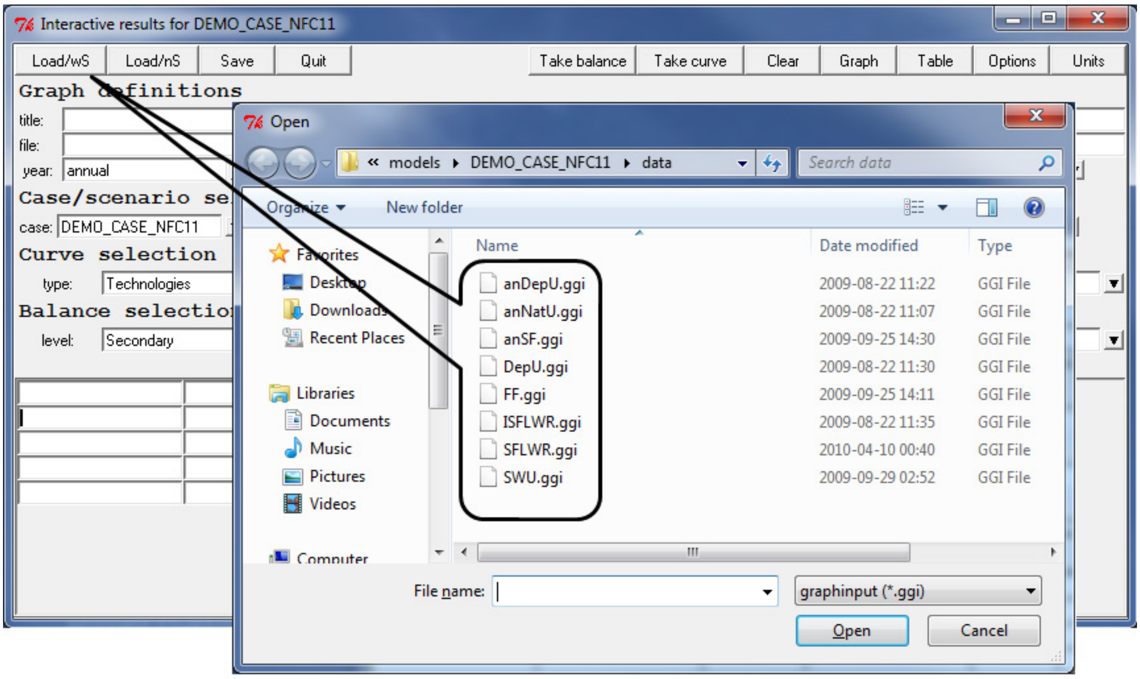
DEMO_CASE_NFC11, adb: Graph 6

Region: DEMO_CASE_NFC11, Scenario: adb
Unit: ton

created: 2015-04-27, 13:33

FIG. 2.28. Accumulation of spent fuel in interim storage.

All these results can be saved for later review. The results for the present example of one unit of an LWR are already saved and can be reloaded (see Fig. 2.29).



title:
file:
year: annual
case: DEMO_CASE_NFC11
type: Technologies
level: Secondary

« models ▸ DEMO_CASE_NFC11 ▸ data

Name	Date modified	Type
anDepU.ggi	2009-08-22 11:22	GGI File
anNatU.ggi	2009-08-22 11:07	GGI File
anSF.ggi	2009-09-25 14:30	GGI File
DepU.ggi	2009-08-22 11:30	GGI File
FF.ggi	2009-09-25 14:11	GGI File
ISFLWR.ggi	2009-08-22 11:35	GGI File
SFLWR.ggi	2010-04-10 00:40	GGI File
SWU.ggi	2009-09-29 02:52	GGI File

File name:
graphinput (*.ggi)

FIG. 2.29. File name of results selected and saved.

2.1.4. Economic results of MESSAGE modelling

The cap utility can be used to compile and extract the economic results, which provides the user with more flexibility for compiling and tabulating the results. To use the cap utility, an input file has to be prepared to specify the results to be extracted. For example, such an input file has already been prepared that can generate three tables (see Fig. 2.30):

- — Annual investments in the NPP;
- — Annual expenditure on the total fuel cycle and on operation and maintenance (O&M) of the NPP;
- — LUAC&LUOM (see Eq. (2.8)).

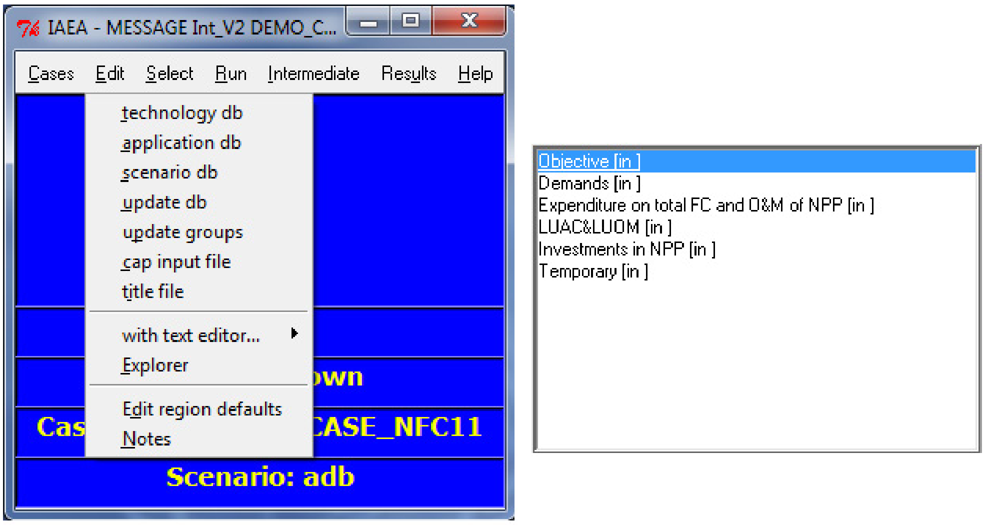


FIG. 2.30. *Window for opening a cin file and tables for economic results.*

Levelized unit energy cost (LUEC) is equivalent to the average price that would have to be paid by consumers to repay (compensate) exactly the costs for capital, O&M and fuel, with an appropriate discount rate. LUEC could be distributed in the three terms:

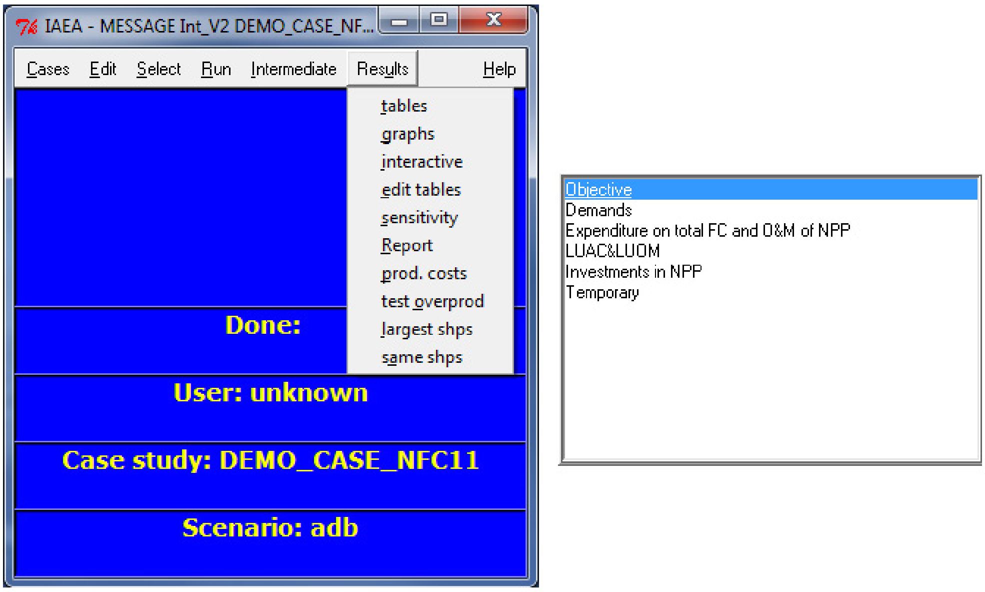
$$\mathrm{LUEC} = \mathrm{LUAC} + \mathrm{LUOM} + \mathrm{LUFC} \tag{2.8}$$

where

LUAC is the levelized unit lifecycle amortization cost;
LUOM is the levelized unit lifecycle operation and maintenance cost;

and LUFC is the levelized unit lifecycle fuel cost.

After executing the cap utility, the results can be viewed from the MESSAGE main window, in the drop-down menu of the tab labelled *Results* command. Selecting *tables* opens a window to select a scenario and its result tables (see Fig. 2.31). Selecting a table name opens the table in a separate window.



Done:

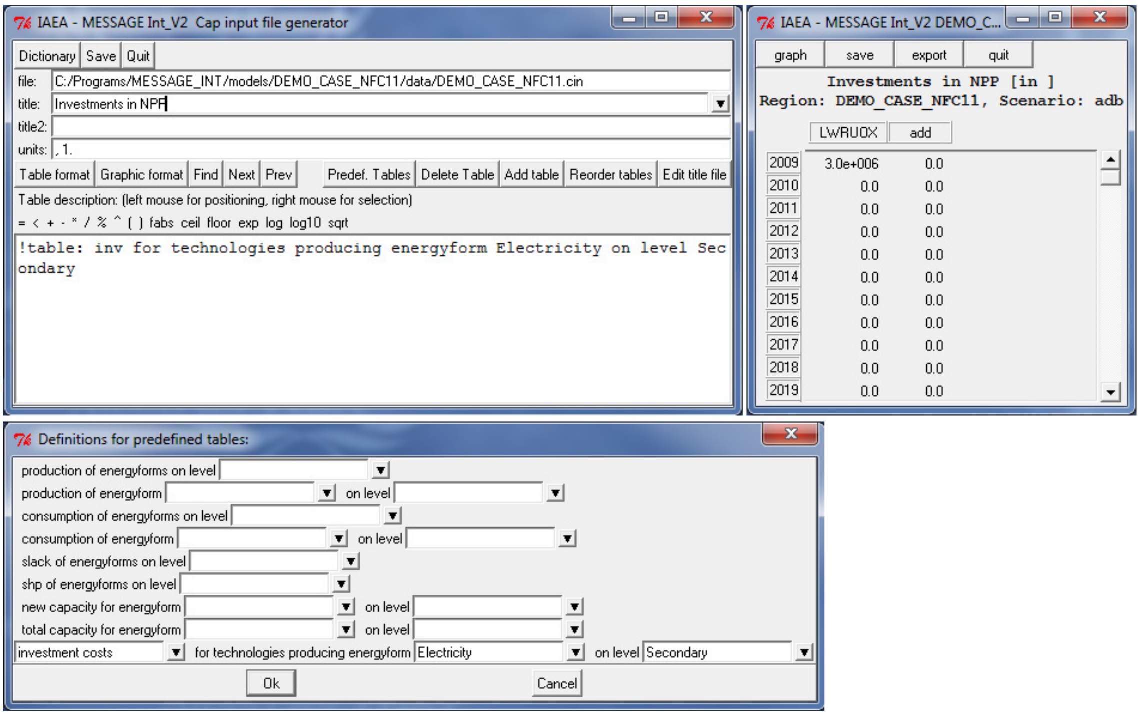
User: unknown

Case study: DEMO_CASE_NFC11

Scenario: adb

FIG. 2.31. Window for selecting a table in a cin file.

Annual investments in the NPP are given in Fig. 2.32, as prepared with predefined tables. Selecting the tab labelled *Predef. Tables* shows the template, and investment costs for technologies producing energy form electricity at the secondary level were selected. Investments and other costs are measured in thousands of US dollars, since capacity has the unit MW, whereas overnight cost has the unit US \$/kW (MW × US \$/kW = US \$1000). The result for annual investment in the LWR is US \$3 billion in 2009 (= 3×10^6 × US \$1000), which is given in the right hand table in Fig. 2.32.



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC11/data/DEMO_CASE_NFC11.cin
title: Investments in NPP
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)
= < + - * / % ^ ( ) fabs ceil floor exp log log10 sqrt

```
!table: inv for technologies producing energyform Electricity on level Sec
ondary
```

Investments in NPP [in]
Region: DEMO_CASE_NFC11, Scenario: adb

	LWRUOX	add
2009	3.0e+006	0.0
2010	0.0	0.0
2011	0.0	0.0
2012	0.0	0.0
2013	0.0	0.0
2014	0.0	0.0
2015	0.0	0.0
2016	0.0	0.0
2017	0.0	0.0
2018	0.0	0.0
2019	0.0	0.0

investment costs for technologies producing energyform Electricity on level Secondary

FIG. 2.32. Annual investments in the NPP.

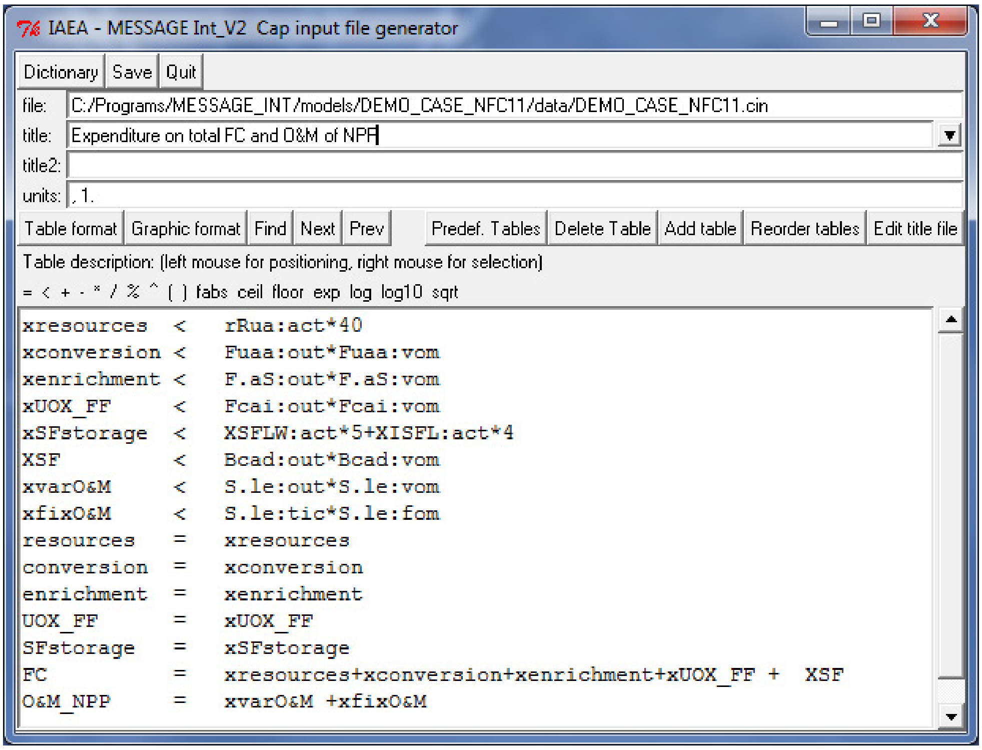
Annual expenditure on the fuel cycle and O&M of the NPP are given in Figs 2.33 and 2.34. The sign < means that the calculation is intermediate and is not shown in the table (see Fig. 2.33). The expenditure on the fuel cycle including resource, conversion, enrichment, fresh fuel fabrication and spent fuel storage was calculated. Expenditure on given fuel cycle step is obtained by multiplication of material amount for given step by corresponding specific cost. For example, annual expenditure on uranium conversion is calculated by the equation:

$$\mathrm{xconversion} = \mathrm{Fuaa{:}out} \times \mathrm{Fuaa{:}vom} \tag{2.9}$$

where

xconversion	is the annual expenditure on uranium conversion (in US $);
Fuaa:out	is the amount of converted uranium (in kg HM);

and Fuaa:vom is the conversion cost per kg HM of converted uranium (in US $/kg HM).



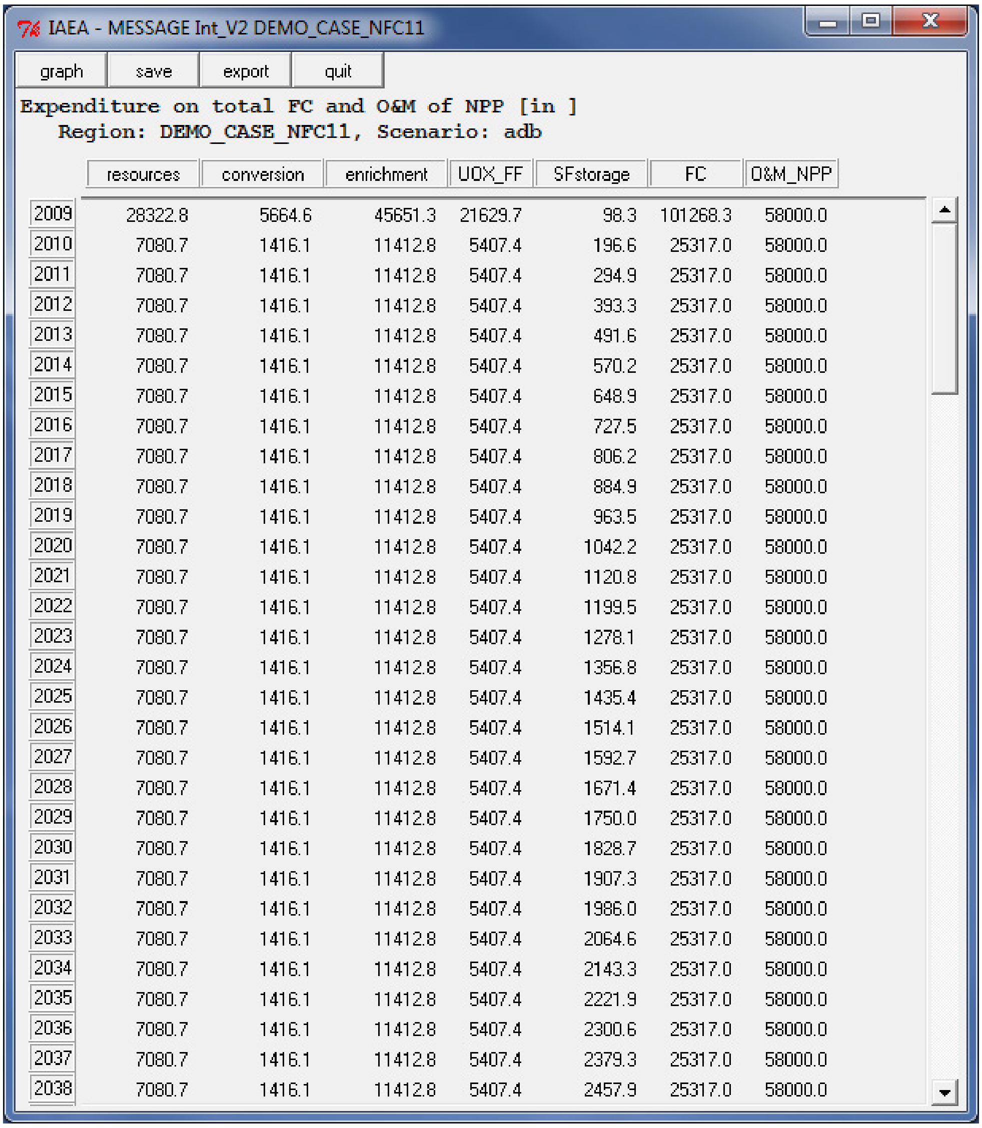
file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC11/data/DEMO_CASE_NFC11.cin
title: Expenditure on total FC and O&M of NPP
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)

= < + - * / % ^ ( ) fabs ceil floor exp log log10 sqrt

```
xresources  <   rRua:act*40
xconversion <   Fuaa:out*Fuaa:vom
xenrichment <   F.aS:out*F.aS:vom
xUOX_FF     <   Fcai:out*Fcai:vom
xSFstorage  <   XSFLW:act*5+XISFL:act*4
XSF         <   Bcad:out*Bcad:vom
xvarO&M     <   S.le:out*S.le:vom
xfixO&M     <   S.le:tic*S.le:fom
resources   =   xresources
conversion  =   xconversion
enrichment  =   xenrichment
UOX_FF      =   xUOX_FF
SFstorage   =   xSFstorage
FC          =   xresources+xconversion+xenrichment+xUOX_FF +  XSF
O&M_NPP     =   xvarO&M +xfixO&M
```

FIG. 2.33. *Annual expenditure on the fuel cycle and O&M of the NPP.*

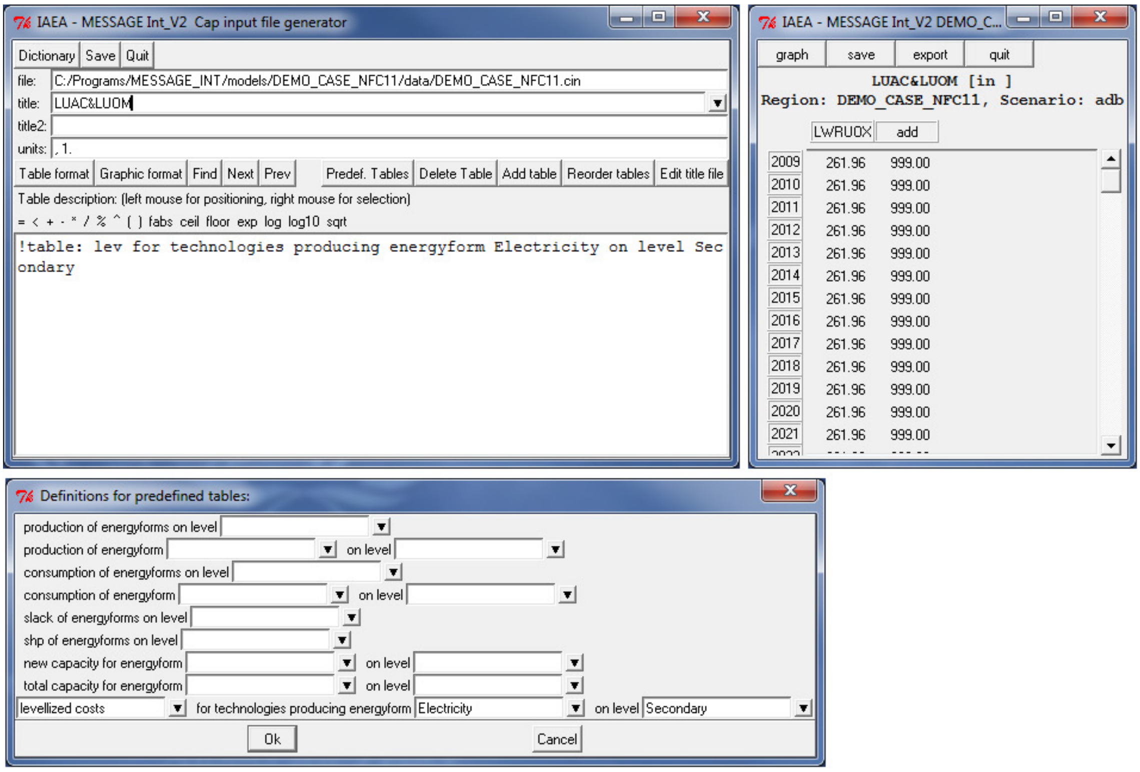


Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC11, Scenario: adb

	resources	conversion	enrichment	UOX_FF	SFstorage	FC	O&M_NPP
2009	28322.8	5664.6	45651.3	21629.7	98.3	101268.3	58000.0
2010	7080.7	1416.1	11412.8	5407.4	196.6	25317.0	58000.0
2011	7080.7	1416.1	11412.8	5407.4	294.9	25317.0	58000.0
2012	7080.7	1416.1	11412.8	5407.4	393.3	25317.0	58000.0
2013	7080.7	1416.1	11412.8	5407.4	491.6	25317.0	58000.0
2014	7080.7	1416.1	11412.8	5407.4	570.2	25317.0	58000.0
2015	7080.7	1416.1	11412.8	5407.4	648.9	25317.0	58000.0
2016	7080.7	1416.1	11412.8	5407.4	727.5	25317.0	58000.0
2017	7080.7	1416.1	11412.8	5407.4	806.2	25317.0	58000.0
2018	7080.7	1416.1	11412.8	5407.4	884.9	25317.0	58000.0
2019	7080.7	1416.1	11412.8	5407.4	963.5	25317.0	58000.0
2020	7080.7	1416.1	11412.8	5407.4	1042.2	25317.0	58000.0
2021	7080.7	1416.1	11412.8	5407.4	1120.8	25317.0	58000.0
2022	7080.7	1416.1	11412.8	5407.4	1199.5	25317.0	58000.0
2023	7080.7	1416.1	11412.8	5407.4	1278.1	25317.0	58000.0
2024	7080.7	1416.1	11412.8	5407.4	1356.8	25317.0	58000.0
2025	7080.7	1416.1	11412.8	5407.4	1435.4	25317.0	58000.0
2026	7080.7	1416.1	11412.8	5407.4	1514.1	25317.0	58000.0
2027	7080.7	1416.1	11412.8	5407.4	1592.7	25317.0	58000.0
2028	7080.7	1416.1	11412.8	5407.4	1671.4	25317.0	58000.0
2029	7080.7	1416.1	11412.8	5407.4	1750.0	25317.0	58000.0
2030	7080.7	1416.1	11412.8	5407.4	1828.7	25317.0	58000.0
2031	7080.7	1416.1	11412.8	5407.4	1907.3	25317.0	58000.0
2032	7080.7	1416.1	11412.8	5407.4	1986.0	25317.0	58000.0
2033	7080.7	1416.1	11412.8	5407.4	2064.6	25317.0	58000.0
2034	7080.7	1416.1	11412.8	5407.4	2143.3	25317.0	58000.0
2035	7080.7	1416.1	11412.8	5407.4	2221.9	25317.0	58000.0
2036	7080.7	1416.1	11412.8	5407.4	2300.6	25317.0	58000.0
2037	7080.7	1416.1	11412.8	5407.4	2379.3	25317.0	58000.0
2038	7080.7	1416.1	11412.8	5407.4	2457.9	25317.0	58000.0

FIG. 2.34. *Annual expenditure on the fuel cycle and O&M of the NPP.*

Data calculated are given in the right hand table in Fig. 2.35. Annual expenditure on O&M of the NPP (fixed and variable O&M) was also included in this table. Costs and investment are measured in thousands of US dollars. LUAC and LUOM costs for an LWR was prepared with the help of the tab labelled *Predef. Tables*. The result is US $261.96/kW·a.



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC11/data/DEMO_CASE_NFC11.cin
title: LUAC&LUOM
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)

```
!table: lev for technologies producing energyform Electricity on level Sec
ondary
```

```
LUAC&LUOM [in ]
Region: DEMO_CASE_NFC11, Scenario: adb
```

	LWRUOX	add
2009	261.96	999.00
2010	261.96	999.00
2011	261.96	999.00
2012	261.96	999.00
2013	261.96	999.00
2014	261.96	999.00
2015	261.96	999.00
2016	261.96	999.00
2017	261.96	999.00
2018	261.96	999.00
2019	261.96	999.00
2020	261.96	999.00
2021	261.96	999.00

levellized costs for technologies producing energyform Electricity on level Secondary

FIG. 2.35. LUAC and LUOM costs.

2.2. A GLOBAL NES BASED ON AN LWR AND AN HWR WITH A ONCE THROUGH FUEL CYCLE (DEMO_CASE_NFC12)

The MESSAGE model illustrates the application of MESSAGE for modelling an NES based on thermal reactors with a once through fuel cycle at a global level. The model provides an optimal structure for nuclear power development and allows the optimal schedule to be assessed for the introduction of various reactor technologies and fuel cycle options, infrastructure facilities, nuclear material flows and wastes, investments and other costs.

The reactors and fuels to be considered for this section are HWRs using natural uranium fuel, LWRs using UOX fuel and ALWRs using UOX fuel. The model is set to start in 2009 and end in 2160. A projection of nuclear demand growth is based on an average of all scenarios of the Intergovernmental Panel on Climate Change. Nuclear demand growth is 297.6 GW(e)·a in 2008, 700 GW(e)·a in 2030, 1500 GW(e)·a in 2050, 5000 GW(e)·a in 2100 and constant after that year until the end of the modelling time period. The demand growths for the time periods 2008–2030, 2030–2050 and 2050–2100 are linear interpolated. Beyond 2100, the demand remains constant at 5000 GW(e)·a. Historical capacities of NPPs from 1970 to 2008 are presented in both reactor types, LWRs and HWRs (see Fig. 2.36). The demand for HWRs is assumed to be 6% of the total demand for thermal reactors from 2008 until the end of the modelling period. ALWRs will be introduced from 2015. Data on historical development of LWRs and HWRs come from the Power Reactor Information System. The spent fuel is stored temporarily in this scenario.

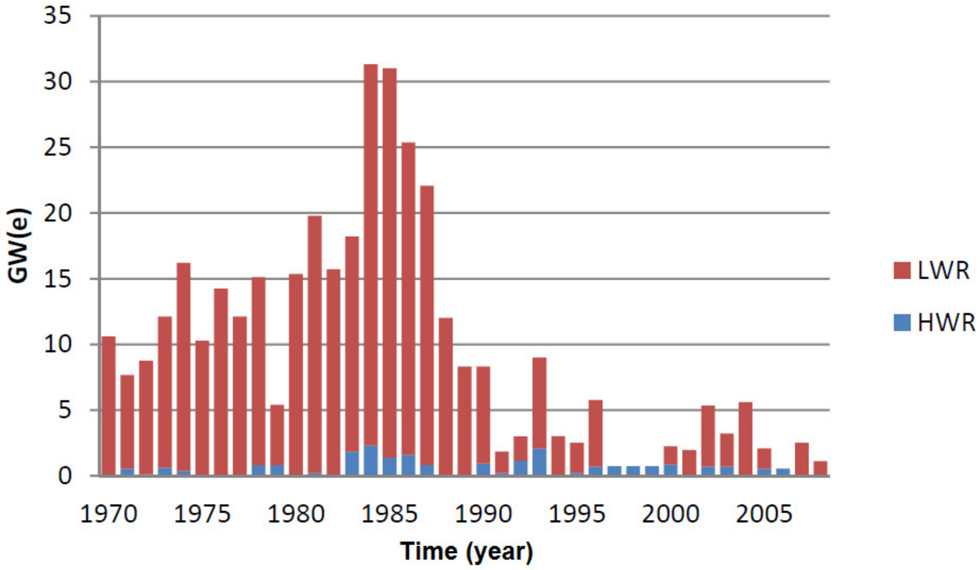


FIG. 2.36. Historical capacities.

Data on uranium resources were taken from the 2014 edition of the Red Book [2.1]. All resources are divided into five grades (a–e). Grades a–c are associated with known and undiscovered resources. Natural uranium resources are restricted to 16 million tonnes for the sum of these grades. Grade d is associated with uranium in phosphates and has a resource of 22 million tonnes, with a cost of recovery of more than US $350/kg U. Natural uranium resources are restricted to 38 million tonnes for the sum of grades a–d. Grade e is associated with uranium in sea water. It is assumed that grade e has a practically unlimited resource, with a cost recovery of more than US $350/kg U (see Table 2.6).

TABLE 2.6. URANIUM RESOURCES ACCORDING TO GRADE

Grade	US $/kg	Resource ('000 t)	Total ('000 t)
a: Known and undiscovered resources	40	2 970	16 053
b: Known and undiscovered resources	80	3 746	
c: Known and undiscovered resources	130	9 337	
d: Phosphates	>350	22 000	38 053
e: Sea water	>350	unlimited	unlimited

Table 2.7 shows some technical characteristics of existing and advanced reactors. Typical characteristics were used for existing LWRs and HWRs. Improved technical characteristics (more burn up and enrichment) were used for ALWRs.

TABLE 2.7. REACTOR CHARACTERISTICS

Item	Unit	LWR	ALWR	HWR
Nuclear capacity	GW(e)	1	1.5	0.6
Thermal efficiency	n.a.[a]	0.33	0.34	0.30
Load factor	n.a.[a]	0.8	0.8	0.8
Plant lifetime	a	40	60	40
Discharged burnup	GW·d/t HM	45	60	7
Construction time	a	5	5	5
Enrichment of fresh fuel	n.a.[a]	0.040	0.049	0.007 114
Cooling time	a	5	5	5

[a] n.a.: not applicable.

Economic data for reactors and their fuel cycle are given in Tables 2.8 and 2.9. Investment (US $3000/kW(e)) for an LWR is approximately 14% less than for an HWR (US $3500/kW(e)) (see Table 2.8). Decommissioning cost is included in fix O&M cost. Fuel cycle front end and back end requirements are considered as service with corresponding service cost (see Table 2.9). The discount rate is 4%.

TABLE 2.8. REACTOR COSTS

Item	Unit	Reactor type	Reference value
Investment cost	US $/kW(e)	LWR	3000
		HWR	3500
Fixed O&M cost	US $/kW/a	LWR	50
		HWR	55
Variable O&M cost	US $/kW·a	LWR	10
		HWR	15

TABLE 2.9. FUEL CYCLE COSTS

Item	Unit	Type	Reference value
Conversion	US $/kg U	LWR, HWR	8
Enrichment	US $/kg SWU	LWR UOX	110
Fuel fabrication	US $/kg HM	LWR UOX HWR UOX	275 65
Storage	US $/kg HM/a	LWR UOX HWR UOX	5 4

The average annual nuclear material flow for each step of a nuclear fuel cycle option in each reactor type can be estimated based on the technical reactor and fuel cycle data (see Table 2.7) and Eqs (2.1)–(2.7), in Section 2.1.1. The scheme of the nuclear fuel cycle is given in the Fig. 2.37. For simplicity, cooling and interim storage are modelled as one storage function.

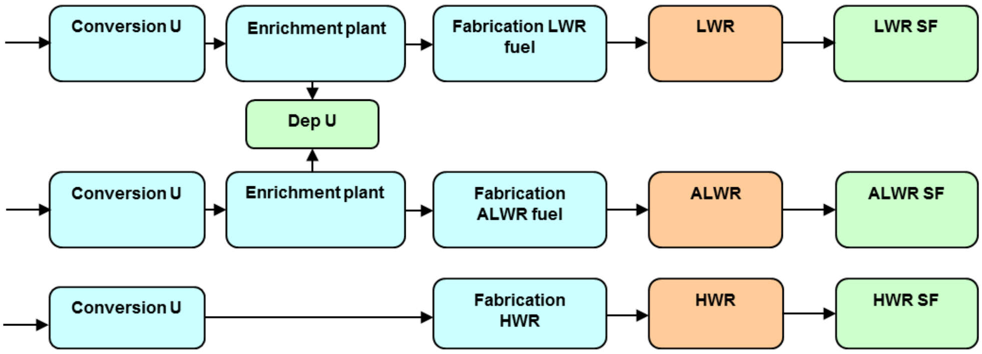
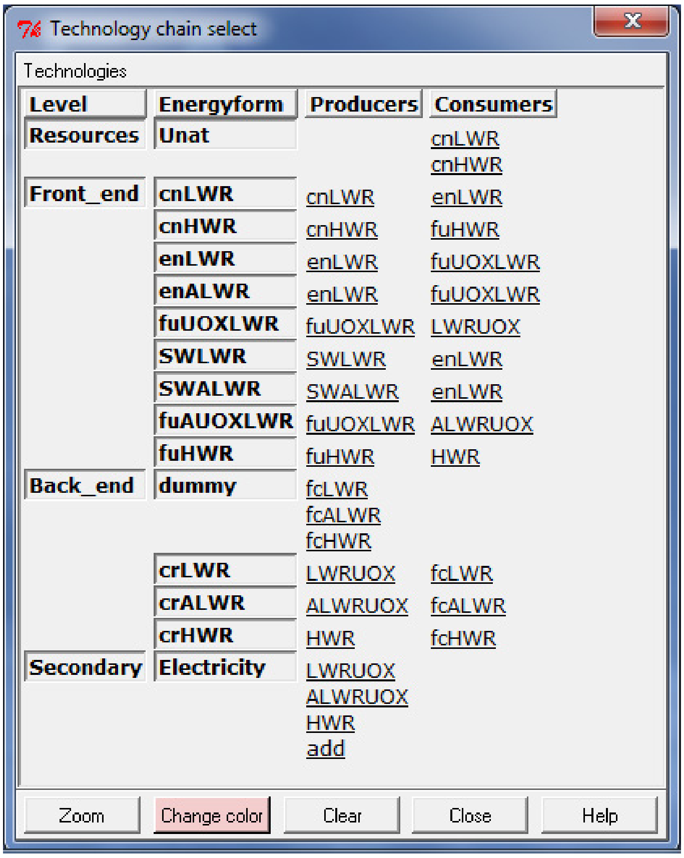


FIG. 2.37. Scheme of global once through fuel cycle based on thermal reactors.

The MESSAGE energy chain of the NES is shown in Fig. 2.38. Preparation of input data for HWR and ALWR reactors and associated storages in MESSAGE format can be done similarly as for LWR.



Level	Energyform	Producers	Consumers
Resources	Unat		cnLWR cnHWR
Front_end	cnLWR	cnLWR	enLWR
	cnHWR	cnHWR	fuHWR
	enLWR	enLWR	fuUOXLWR
	enALWR	enLWR	fuUOXLWR
	fuUOXLWR	fuUOXLWR	LWRUOX
	SWLWR	SWLWR	enLWR
	SWALWR	SWALWR	enLWR
	fuAUOXLWR	fuUOXLWR	ALWRUOX
	fuHWR	fuHWR	HWR
Back_end	dummy	fcLWR fcALWR fcHWR	
	crLWR	LWRUOX	fcLWR
	crALWR	ALWRUOX	fcALWR
	crHWR	HWR	fcHWR
Secondary	Electricity	LWRUOX ALWRUOX HWR add	

FIG. 2.38. Energy chain of the NES.

2.2.1. Mass flow MESSAGE outputs for an open fuel cycle

After running MESSAGE Demo_Case_NFC12, several results can be selected and displayed in the interactive mode. In this example, the following results are extracted and analysed:

— Nuclear electricity generation structure (Electr.ggi);
— Natural uranium consumption (cumNatU.ggi);
— Fresh fuel requirements (FF.ggi);
— SWU consumption (SWU.ggi);
— Spent nuclear fuel in storages (SF.ggi).

Nuclear electricity generation structure is displayed in Fig. 2.39. It follows from the calculations that the ALWR will be commissioned from 2015 because the ALWR is cheaper than the LWR. As a result, the LWR will be replaced by the ALWR towards the end of its lifetime. According to this scenario, the demand for an HWR would be 6% of the total demand.

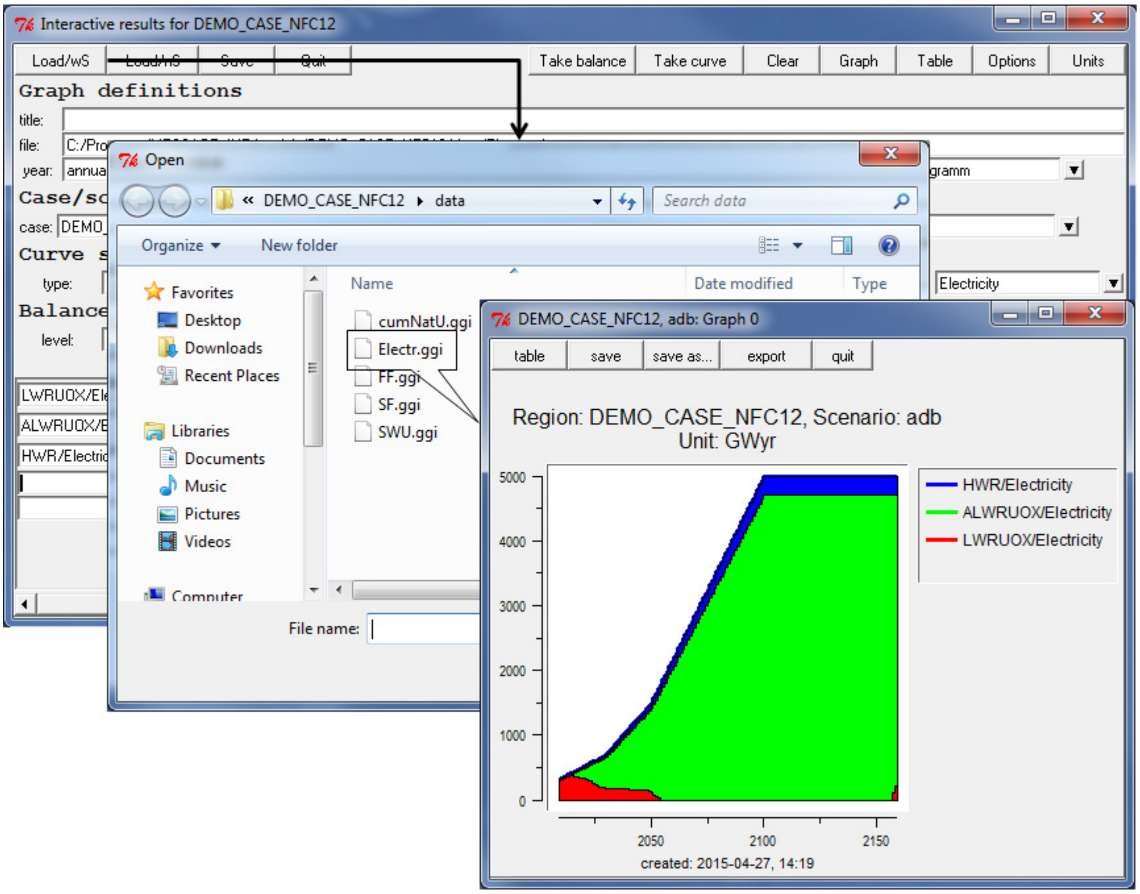


FIG. 2.39. Nuclear electricity generation structure.

The consumption of natural uranium over a 100 year period would be about 38 million tonnes (see Fig. 2.40). Ultimate (identified, prognosticated and speculative) uranium resources are estimated at 16 million tonnes. Cumulative uranium demand will reach ultimate resource by 2070. After that time, uranium recovered from phosphates will be used until it is exhausted in 2100, and then natural uranium from sea water will be used.

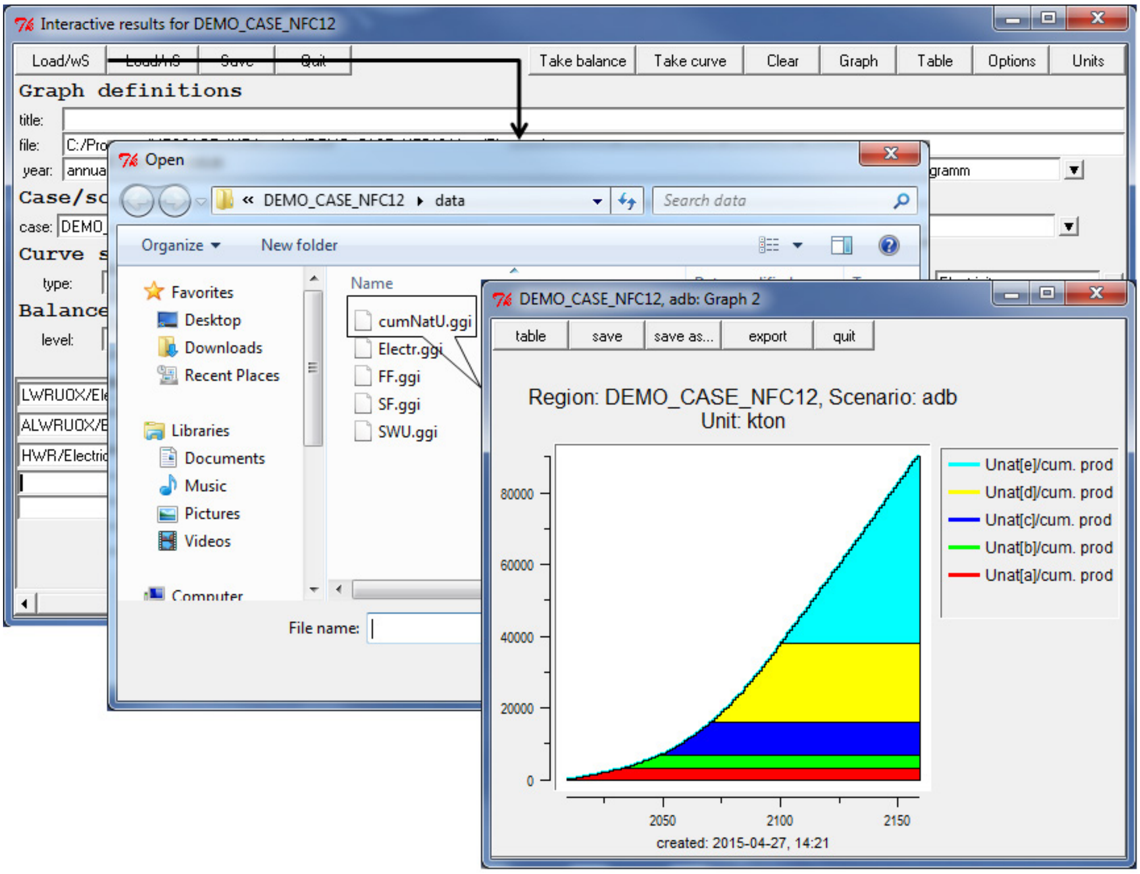


FIG. 2.40. Natural uranium consumption.

By the end of the century, annual ALWR and HWR fresh fuel requirements will be 52 000 t HM and 93 000 t HM, respectively (see Fig. 2.41), while SWU requirements will be 800 000 t SWU/a (see Fig. 2.42).

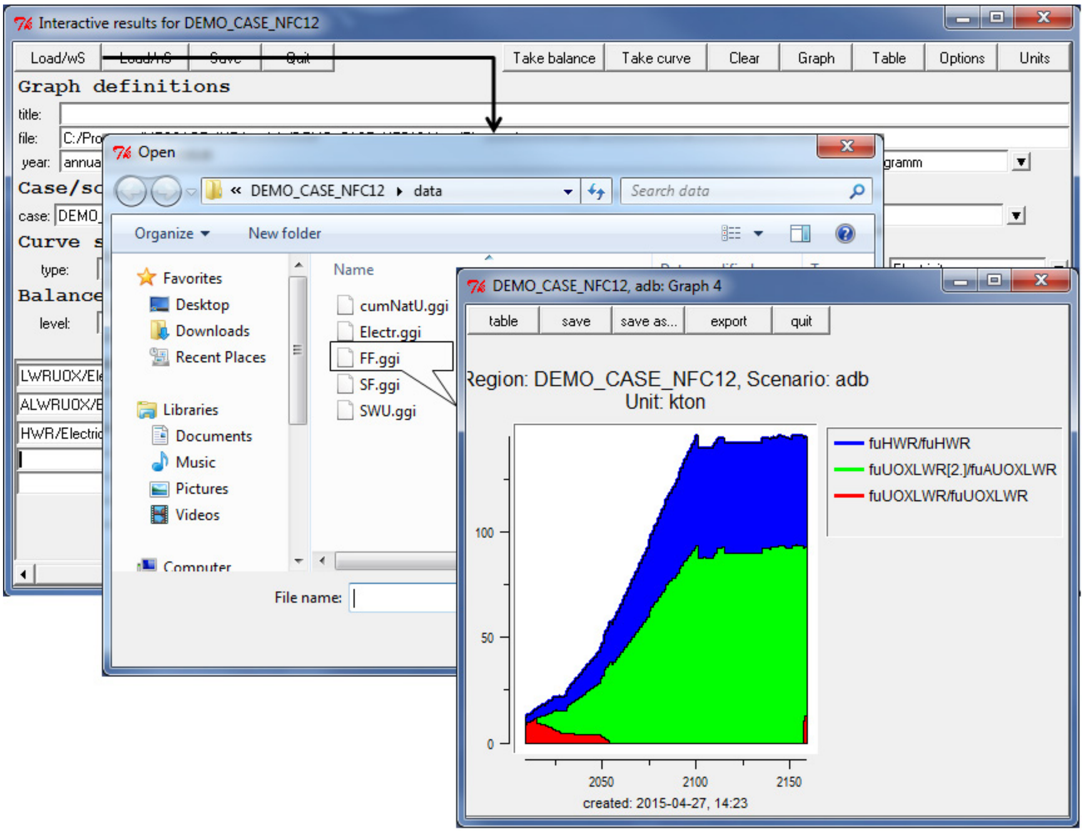


FIG. 2.41. *Fresh fuel requirements.*

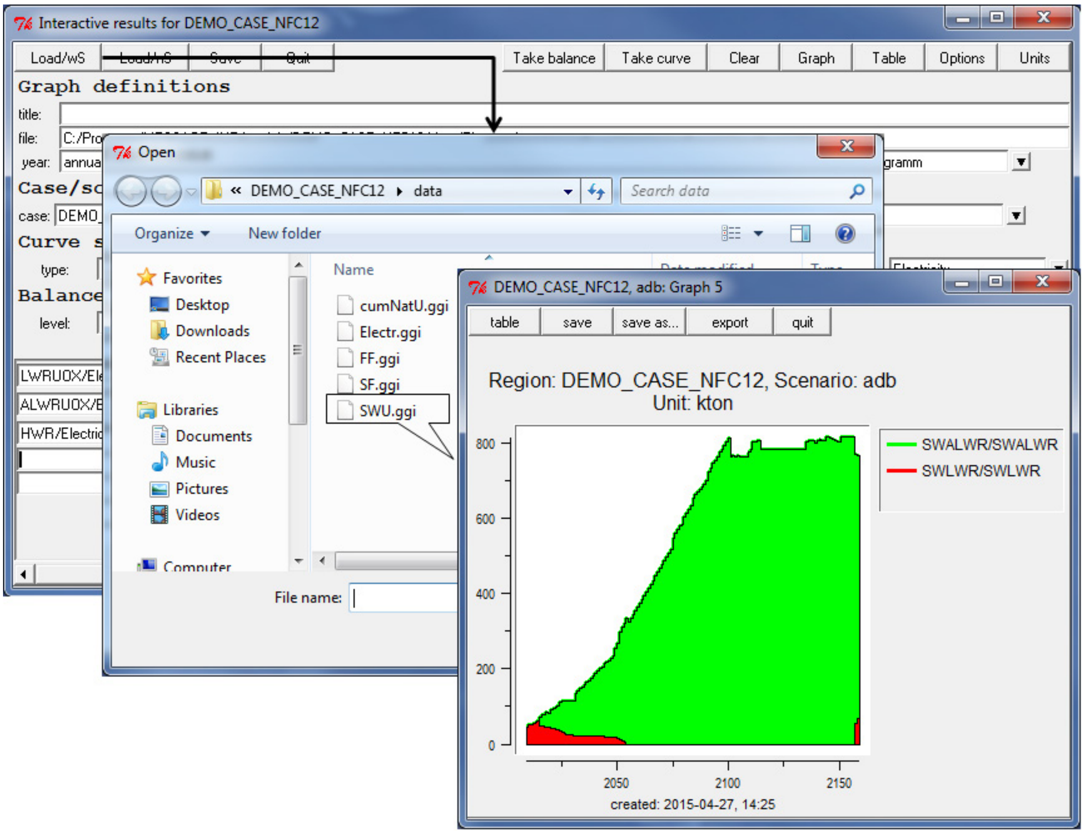


FIG. 2.42. *SWU consumption.*

Figure 2.43 shows the accumulation of spent fuel in interim storage, which is very high. As a comparison, the capacities of operating spent fuel storage facilities and storage facilities under construction have a total volume of approximately 270 000 tonnes. The total amount of cumulative spent fuel will reach 5.7 million tonnes by 2100. It means that 80 repositories with the capacity of Yucca Mountain repository (about 70 000 t) should be built by 2100. In this scenario, a significant amount of plutonium will accrue as well. Thus, spent fuel management may be a major challenge in the future.

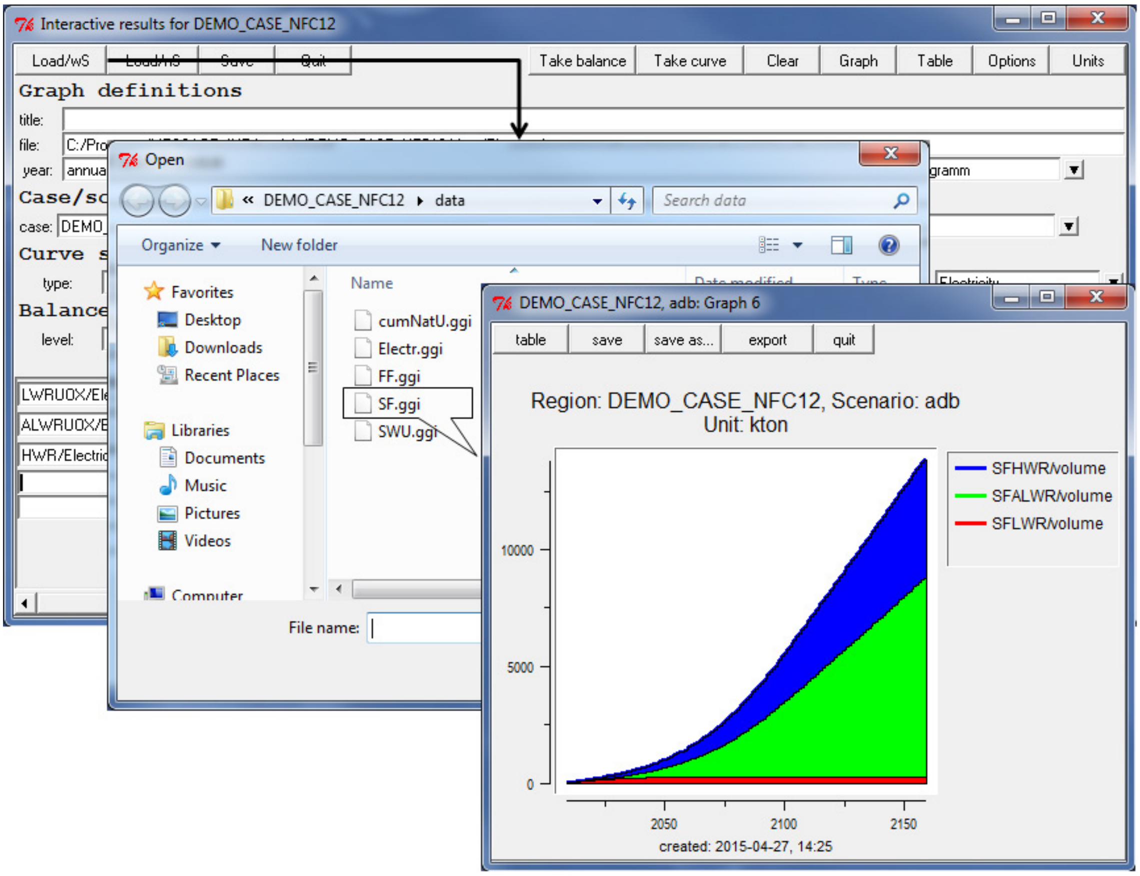


FIG. 2.43. Spent nuclear fuel in storage.

2.2.2. Note about boundary effects

The previous scenario is now considered with one changed assumption: the demand for an HWR is set at more than 6% of the total demand for thermal reactors from 2008 until the end of the modelling period (in the previous scenario, it was assumed to be precisely 6%). The ALWR is cheaper than the HWR, so the same nuclear power structure can be obtained (see Fig. 2.44). Nevertheless, HWR electricity generation is increased by the end of the time period. This represents a pseudo effect with respect to boundaries. If new reactor capacity is built in one of the last periods, its lifetime can exceed the calculation horizon. This factor is mitigated by reducing the investment costs, which in this example leads to boundary effects for the later periods of the technology's lifetime. The interval up to 2100 is therefore considered as the prognosis in this case study and is extended up to 2160 on the account of the boundary effects of linear modelling.

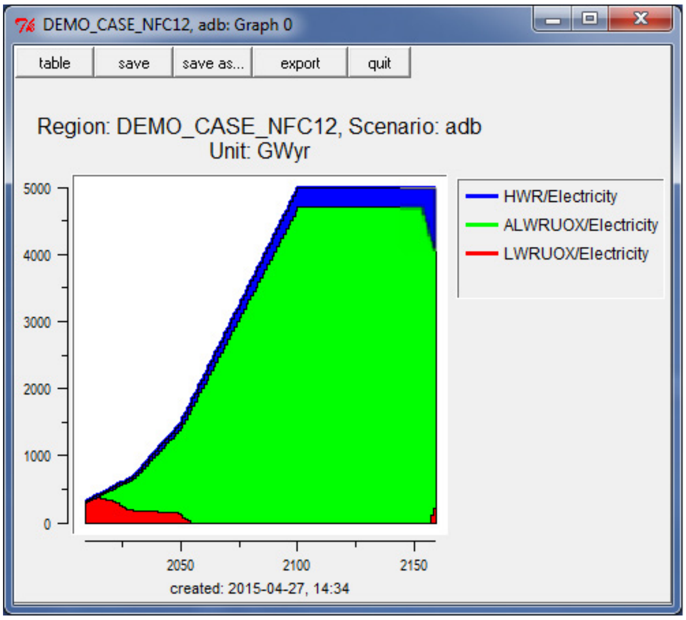


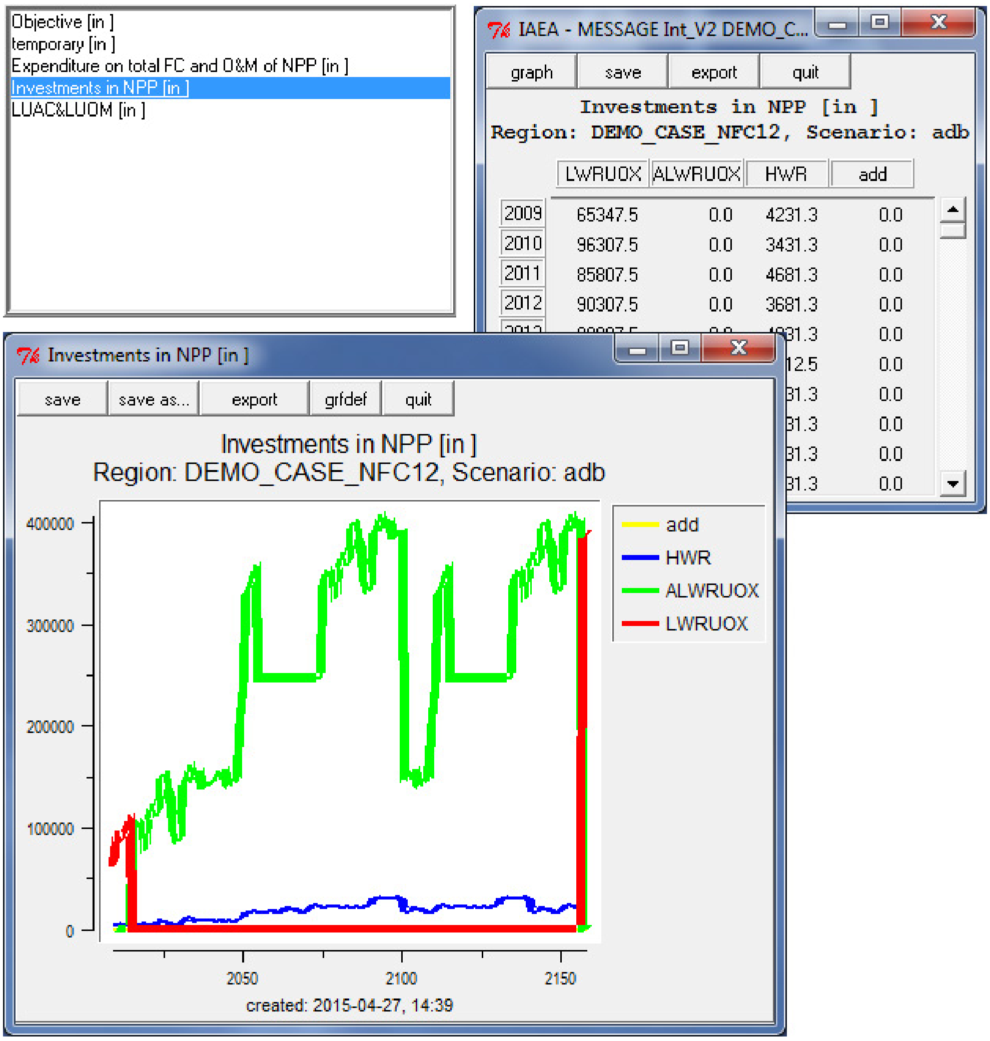
FIG. 2.44. *Illustration of the boundary effects for a nuclear electricity generation structure.*

2.2.3. Economic results of MESSAGE modelling for an open fuel cycle

The economic results can be extracted through a cin file. Three tables were prepared to calculate the following results:

- — Annual investments in the NPP;
- — Annual expenditure on the fuel cycle and O&M of the NPP;
- — LUAC&LUOM.

Annual investments in the NPP are given in Fig. 2.45. The table was prepared using the tab labelled *Predef. Tables*. Investments and other costs are measured in millions of US dollars, since capacity has the unit GW and overnight cost has the unit US $/kW (GW × US $/kW = US $ 1 million). The results for annual investment in the LWR, ALWR and HWR are given in the graph in Fig. 2.45.



Objective [in]
temporary [in]
Expenditure on total FC and O&M of NPP [in]
Investments in NPP [in]
LUAC&LUOM [in]

IAEA - MESSAGE Int_V2 DEMO_C...

Investments in NPP [in]
Region: DEMO_CASE_NFC12, Scenario: adb

	LWRUOX	ALWRUOX	HWR	add
2009	65347.5	0.0	4231.3	0.0
2010	96307.5	0.0	3431.3	0.0
2011	85807.5	0.0	4681.3	0.0
2012	90307.5	0.0	3681.3	0.0

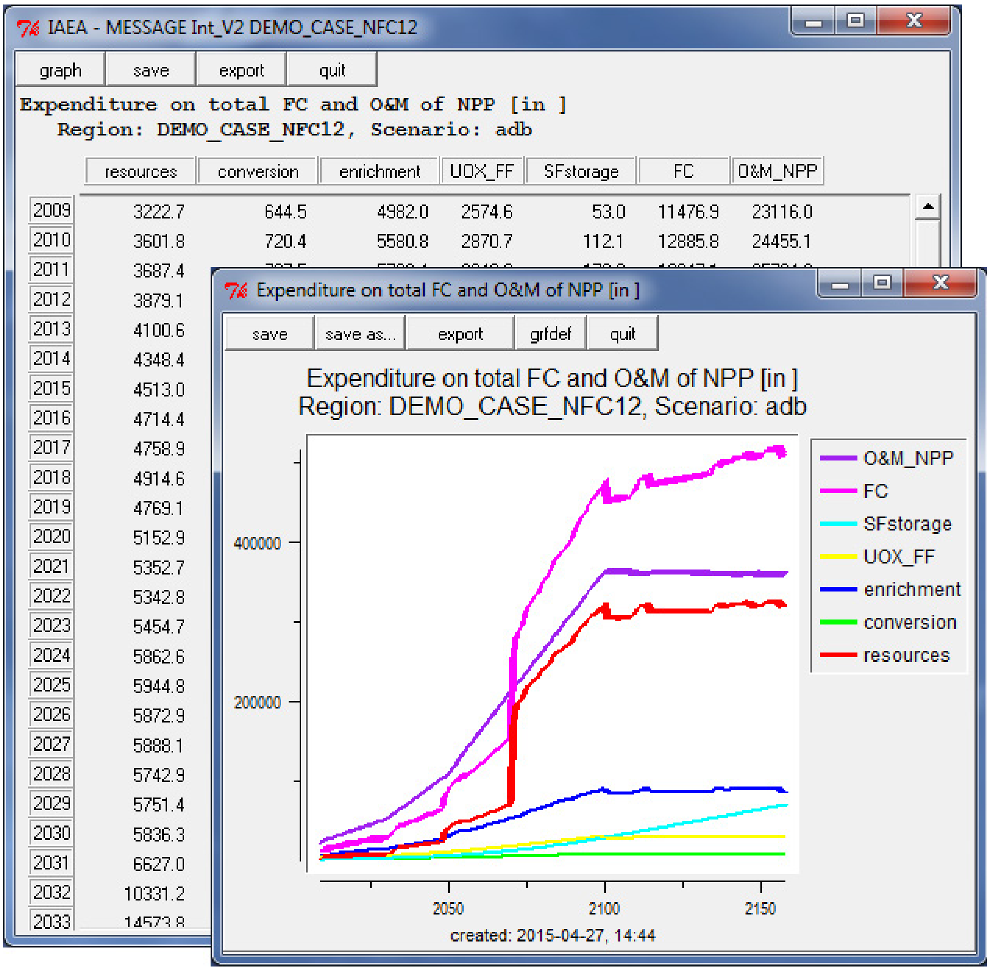
Investments in NPP [in]

Investments in NPP [in]
Region: DEMO_CASE_NFC12, Scenario: adb

created: 2015-04-27, 14:39

FIG. 2.45. Annual investments in the NPP.

Annual expenditure on the fuel cycle and O&M of the NPP are given in Fig. 2.46. The expenditure on the fuel cycle includes resource, conversion, enrichment, fresh fuel fabrication and spent fuel storage costs. Annual expenditure on O&M of the NPP (fixed and variable O&M) was also calculated. Costs and investment are measured in millions of US dollars.



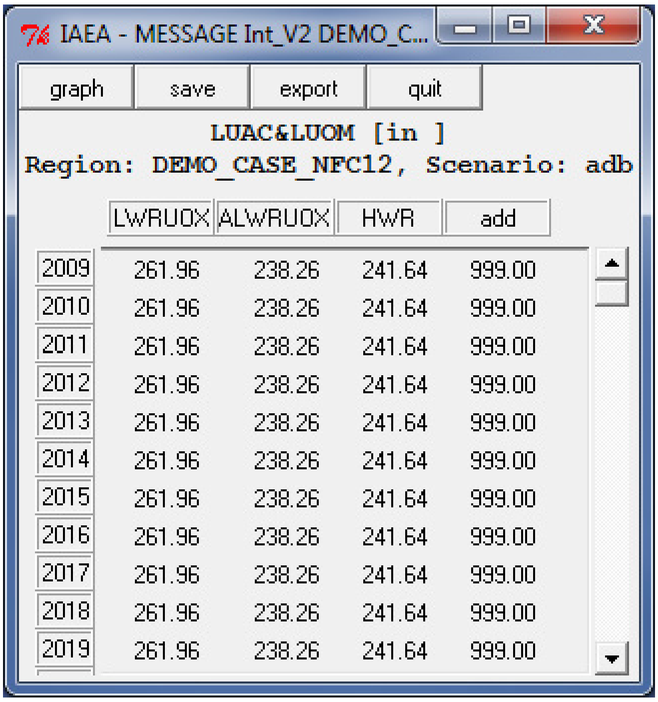
Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC12, Scenario: adb

	resources	conversion	enrichment	UOX_FF	SFstorage	FC	O&M_NPP
2009	3222.7	644.5	4982.0	2574.6	53.0	11476.9	23116.0
2010	3601.8	720.4	5580.8	2870.7	112.1	12885.8	24455.1
2011	3687.4						
2012	3879.1						
2013	4100.6						
2014	4348.4						
2015	4513.0						
2016	4714.4						
2017	4758.9						
2018	4914.6						
2019	4769.1						
2020	5152.9						
2021	5352.7						
2022	5342.8						
2023	5454.7						
2024	5862.6						
2025	5944.8						
2026	5872.9						
2027	5888.1						
2028	5742.9						
2029	5751.4						
2030	5836.3						
2031	6627.0						
2032	10331.2						
2033	14573.8						

Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC12, Scenario: adb

FIG. 2.46. Annual expenditure on the fuel cycle and O&M of the NPP.

LUAC&LUOM for the NPP was prepared with the help of the tab labelled *Predef. Tables*. The results in US $/kW·a are 261.96, 238.26 and 241.64 for an LWR, an ALWR and an HWR, respectively (see Fig. 2.47).



LUAC&LUOM [in]
Region: DEMO_CASE_NFC12, Scenario: adb

	LWRUOX	ALWRUOX	HWR	add
2009	261.96	238.26	241.64	999.00
2010	261.96	238.26	241.64	999.00
2011	261.96	238.26	241.64	999.00
2012	261.96	238.26	241.64	999.00
2013	261.96	238.26	241.64	999.00
2014	261.96	238.26	241.64	999.00
2015	261.96	238.26	241.64	999.00
2016	261.96	238.26	241.64	999.00
2017	261.96	238.26	241.64	999.00
2018	261.96	238.26	241.64	999.00
2019	261.96	238.26	241.64	999.00

FIG 2.47. LUAC&LUOM for the NPP.

REFERENCE TO SECTION 2

[2.1] OECD NUCLEAR ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2014: Resources, Production and Demand, OECD, Paris (2014).

3. DEMONSTRATION CASE 2: AN NES BASED ON THERMAL REACTORS WITH REPROCESSING

This demonstration models a partially closed fuel cycle based on thermal reactors with plutonium mono-recycling. The modelling considers two fuel types: UOX and MOX. UOX fuel can be fabricated using natural uranium or reprocessed uranium, while MOX fuel is fabricated from reprocessed plutonium and depleted uranium. In this case, only UOX fuel is reprocessed, with the recovery of plutonium and uranium. The reactor uses MOX fuel for about one third of its core fuel. MOX fuel is stored temporarily without reprocessing.

The modelling of a partially closed fuel cycle based on thermal reactors is divided into the following parts:

— A partially closed fuel cycle with one unit of an LWR_MOX without the recycling of reprocessed uranium;
— A partially closed fuel cycle with one unit of an LWR_MOX with the recycling of reprocessed uranium;
— A global NES based on an LWR, an HWR and an LWR_MOX with a partially closed fuel cycle.

3.1. A PARTIALLY CLOSED FUEL CYCLE WITH ONE UNIT OF AN LWR_MOX WITHOUT THE RECYCLING OF REPROCESSED URANIUM

The model simulates an LWR_MOX unit which is assumed to have 1000 MW(e) of installed capacity and a capacity factor of 80%. The time period for this case is 2009–2160, with a constant demand of 800 MW·a. The LWR_MOX uses two fuel types: one third MOX and two thirds UOX. A single recycle of plutonium in the form of MOX fuel is also assumed. There is no recycling of recovered uranium (see Fig. 3.1).

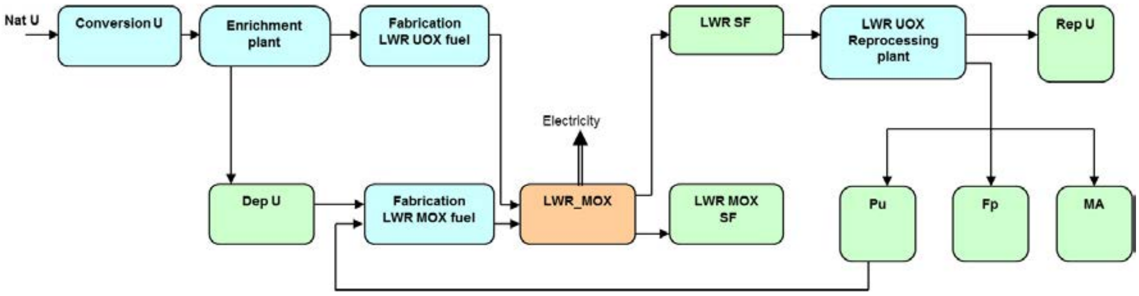


FIG. 3.1. An LWR_MOX fuel cycle diagram.

The technical and economic data of LWR_MOX and its fuel cycle are given in Tables 3.1–3.4. To calculate the input data with the spent fuel reprocessing option, it is necessary to specify the isotopic composition of spent fuel discharged from the reactor. The isotopic composition of spent fuel changes during the cooling time in NPP storage and reprocessing lag time (known as external fuel cycle time) owing to the radioactive decay of unstable isotopes (^{242}Cm: 0.447 years, ^{244}Cm: 18.1 years, ^{238}Pu: 87.7 years and ^{241}Pu: 14.4 years). Calculations of reprocessed products are based on a nuclide group composition of UOX spent fuel after five years of cooling and one year reprocessing. The decay of plutonium and minor actinides in stock have not been taken into account. Fuel cycle front end requirements (conversion, enrichment and fuel fabrication) are considered as services in this model. Reprocessing is modelled as a facility, and its technical and economic parameters are given in Table 3.4.

TABLE 3.1. REACTOR CHARACTERISTICS

Item	Symbol	Unit	LWR_MOX
Nuclear capacity	NC	GW(e)	1
Thermal efficiency	Eff	n.a.[a]	0.33
Load factor	Lf	n.a.[a]	0.80
Residence time	Tr	EFPD	1 168
Discharged burnup	Bu	GW·d/t HM	45
Plutonium content of MOX fuel	TotPuFF	n.a.[a]	0.072 3
Enrichment of UOX	Enr	n.a.[a]	0.04
Cooling time	Tcool	a	5
Tails assay	Ta	n.a.[a]	0.003

[a] n.a.: not applicable.

TABLE 3.2. NUCLIDE GROUP COMPOSITION OF UOX SPENT FUEL AFTER FIVE YEARS OF COOLING AND ONE YEAR OF REPROCESSING

Component	Symbol	Factor
Uranium total	TotUSF	0.942 19
U-235	U235SF	0.007 96
U-236	U236SF	0.005 19
Plutonium total	TotPuSF	0.009 95
Minor actinides	TotMASF	0.001 46
Fission products	TotFPSF	0.046 40

TABLE 3.3. ECONOMIC PARAMETERS OF LWR_MOX AND ITS FUEL CYCLE

Item	Unit	Reference value
Investment cost	US $/kW(e)	3000
Fixed O&M cost	US $/kW/a	50
Variable O&M cost	US $/kW·a	10
Lifetime	a	40
Construction time	a	5
Conversion	US $/kg U	8
Enrichment	US $/kg SWU	110
Fuel fabrication	US $/kg HM	275
Cooling storage	US $/kg HM/a	5
Interim storage	US $/kg HM/a	4
Reprocessing	US $/kg HM	600
Separated plutonium storage	US $/kg HM/a	2000

TABLE 3.4. TECHNICAL AND ECONOMIC PARAMETERS OF THE REPROCESSING FACILITY

Parameter	Unit	UOX reprocessing
Capacity	t HM/a	1000
Capacity factor of use	%	100
Construction time	a	5
Operational life	a	60
Investment cost	US $/kg SF	5000
Annual operational cost	US $/kg SF/a	400
Total service cost (at 4% discount rate)	US $/kg SF	650
Reprocessing loses (total plutonium)	%	0

3.1.1. Mathematical mass flow calculation for a partially closed fuel cycle with one unit of an LWR_MOX without the recycling of reprocessed uranium

The average annual nuclear material flow for each step of a partially closed fuel cycle (see Fig. 3.1) can be estimated based on the technical and economic data for the reactor and fuel cycle (see Tables 3.1 and 3.2). The following are some analytical equations for mass flow calculations:

(a) Annual UOX fresh fuel loading:

$$\mathrm{FFUOX} = \frac{2}{3} \times \frac{365 \times \mathrm{NC} \times \mathrm{Lf}}{\mathrm{Eff} \times \mathrm{Bu}} \tag{3.1}$$

(b) UOX fuel in core (first loading) FuelInCore UOX:

$$\mathrm{FuelInCore\ UOX} = \frac{2}{3} \times \frac{\mathrm{FFUOX} \times \mathrm{Tr}}{365 \times \mathrm{Lf}} \tag{3.2}$$

(c) Annual MOX fresh fuel loading:

$$\mathrm{FFMOX} = \frac{1}{3} \times \frac{365 \times \mathrm{NC} \times \mathrm{Lf}}{\mathrm{Eff} \times \mathrm{Bu}} \tag{3.3}$$

(d) MOX fuel in core (first loading) FuelInCore MOX:

$$\mathrm{FuelInCore\ MOX} = \frac{1}{3} \times \frac{\mathrm{FFMOX} \times \mathrm{Tr}}{365 \times \mathrm{Lf}} \tag{3.4}$$

(e) Natural uranium consumption:

$$\mathrm{NatU} = \frac{\mathrm{FFUOX} \times (\mathrm{Enr} - \mathrm{Ta})}{0.007114 - \mathrm{Ta}} \tag{3.5}$$

(f) Conversion:

$$\mathrm{Cn} = \mathrm{NatU} \tag{3.6}$$

(g) Separative work unit:

$$\mathrm{SWU} = \mathrm{FFUOX} \times \left(V(\mathrm{Enr}) + V(\mathrm{Ta}) \frac{\mathrm{Enr} - 0.007114}{0.007114 - \mathrm{Ta}} - V(0.007114) \frac{\mathrm{Enr} - \mathrm{Ta}}{0.007114 - \mathrm{Ta}} \right) \tag{3.7}$$

where

$$V(x) = (1 - 2x) \ln\left(\frac{1 - x}{x} \right)$$

(h) Depleted uranium production:

$$\mathrm{DepU} = \mathrm{FFUOX} \times \frac{\mathrm{Enr} - 0.007114}{0.007114 - \mathrm{Ta}} \tag{3.8}$$

(i) Spent fuel discharged:

$$\mathrm{SFDUOX} = \mathrm{FFUOX} \tag{3.9}$$

$$\mathrm{SFDMOX} = \mathrm{FFMOX} \tag{3.10}$$

(j) Spent fuel reprocessing:

$$\mathrm{SFRUOX} = \mathrm{SFDUOX} \tag{3.11}$$

(k) Reprocessed plutonium:

$$\mathrm{RepPu} = \mathrm{SFR} \times \mathrm{TotPuSF} \tag{3.12}$$

(l) Reprocessed plutonium used:

$$\mathrm{RepPuUsed} = \mathrm{FFMOX} \times \mathrm{TotPuFF} \tag{3.13}$$

(m) Minor actinides:

$$\mathrm{RepMA} = \mathrm{SFR} \times \mathrm{TotMASF} \tag{3.14}$$

(n) Fission products:

$$\mathrm{RepFP} = \mathrm{SFR} \times \mathrm{TotFPSF} \tag{3.15}$$

(o) Reprocessed uranium:

$$\mathrm{RepU} = \mathrm{SFR} \times \mathrm{TotUSF} \tag{3.16}$$

The analytical calculations for mass flow of LWR_MOX fuel cycle are based on Eqs (3.1–3.16). The results are given in Table 3.5 and Fig. 3.2.

TABLE 3.5. ANALYTICAL MASS FLOW CALCULATIONS

Annual output parameters	Symbol	Unit	Equation	Analytical result
Fresh fuel UOX	FFUOX	t HM	(3.1)	13.1
Fuel in core UOX	FuelInCore UOX	t HM	(3.2)	52.5
Fresh fuel MOX	FFMOX	t HM	(3.3)	6.6
Fuel in core MOX	FuelInCore MOX	t HM	(3.4)	26.2
Natural uranium	NatU	t HM	(3.5)	118
Conversion	Cn	t HM	(3.6)	118
Separative work unit	SWU	t SWU	(3.7)	69.2
Depleted uranium	DepU	t HM	(3.8)	104.9
Spent fuel UOX discharge	SFDUOX	t HM + t FP	(3.9)	13.1
Spent fuel MOX discharge	SFDMOX	t HM + t FP	(3.10)	6.6
Spent fuel reprocessing UOX	SFRUOX	t HM + t FP	(3.11)	13.1
Reprocessed plutonium	RepPu	t HM	(3.12)	0.13
Reprocessed plutonium used	RepPuUsed	t HM	(3.13)	0.474
Minor actinides	RepMA	t HM	(3.14)	0.019
Fission products	RepFP	t	(3.15)	0.608
Reprocessed uranium	RepU	t HM	(3.16)	12.4

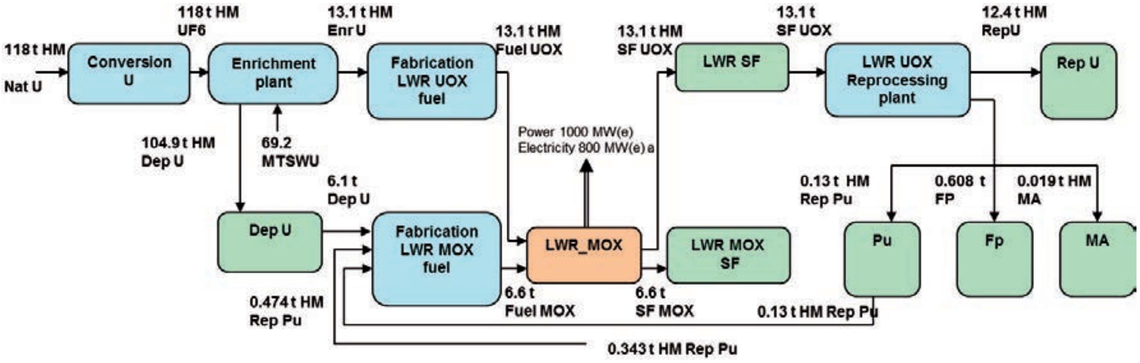
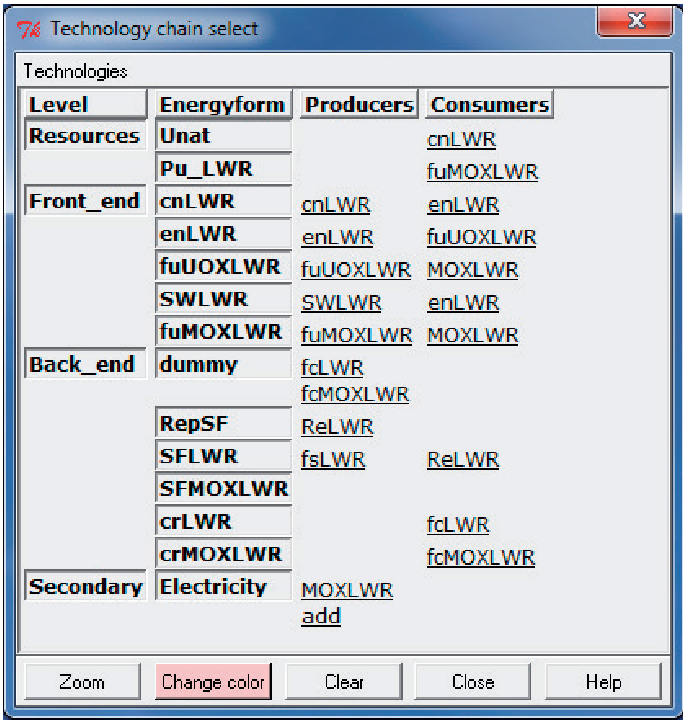


FIG. 3.2. Mass balance of the LWR_MOX fuel cycle.

The LWR_MOX reactor consumes 13.1 t HM of UOX fuel and 6.6 t HM of MOX fuel, discharging the same values of spent fuel. The reprocessing of 13.1 t HM of UOX spent fuel gives 0.13 t HM of plutonium. To produce 6.6 t HM of MOX fuel, 0.474 t HM of reprocessed plutonium is required. This will result in a 0.343 t HM shortfall in plutonium, which should be delivered from the external source.

3.1.2. MESSAGE modelling of a partially closed fuel cycle with one unit of an LWR_MOX without the recycling of reprocessed uranium (Demo_Case_NFC21)

The MESSAGE energy and technology chain for a partially closed fuel cycle option with LWR_MOX without uranium recycling is shown in Fig. 3.3. The technology and storage of the model are given in Table 3.6.



Level	Energyform	Producers	Consumers
Resources	Unat		cnLWR
	Pu_LWR		fuMOXLWR
Front_end	cnLWR	cnLWR	enLWR
	enLWR	enLWR	fuUOXLWR
	fuUOXLWR	fuUOXLWR	MOXLWR
	SWLWR	SWLWR	enLWR
	fuMOXLWR	fuMOXLWR	MOXLWR
Back_end	dummy	fcLWR fcMOXLWR	
	RepSF	ReLWR	
	SFLWR	fsLWR	ReLWR
	SFMOXLWR		
	crLWR		fcLWR
	crMOXLWR		fcMOXLWR
Secondary	Electricity	MOXLWR add	

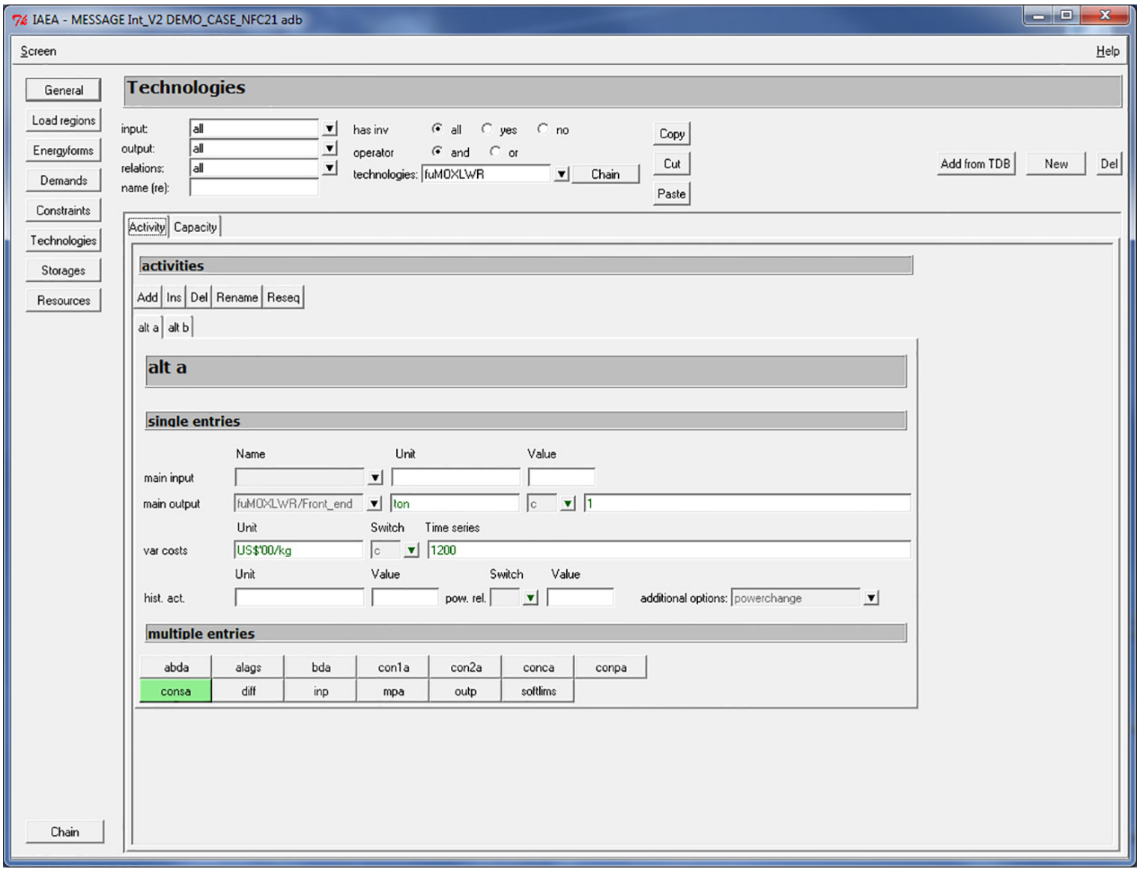
FIG. 3.3. Technology chain.

TABLE 3.6. TECHNOLOGY AND STORAGE USED FOR MODELLING A PARTIALLY CLOSED FUEL CYCLE WITHOUT THE RECYCLING OF REPROCESSED URANIUM

Technology and storage	Explanation
cnLWR	Conversion of uranium in the form of triuranium octoxide (U_3O_8) to uranium hexafluoride (UF_6)
enLWR and SWLWR	Enrichment of uranium
fuUOXLWR	UOX fuel fabrication
fuMOXLWR	MOX fuel fabrication technology
LWR_MOX	LWR using UOX and MOX fuel
fcLWR	Auxiliary technology fcLWR puts discharged fuel to cooling storage SFLWR
fcMOXLWR	Auxiliary technology fcMOXLWR puts discharged fuel to cooling storage SFMOXLWR
fsLWR	Auxiliary technology fsLWR takes UOX spent fuel from UOX storage and puts it on the SFLWR energy form
ReLWR	Reprocessing of UOX spent fuel
DepU	Depleted uranium storage
SFLWR	Storage for UOX spent fuel including cooling and temporary storage
SFMOXLWR	Storage for MOX spent fuel including cooling and temporary storage
Putot	Reprocessed plutonium stock
MAc	Reprocessed minor actinide stock
ReUL	Reprocessed uranium stock
FPr	Separated fission product storage

Conversion, enrichment and UOX fuel fabrication technologies can be modelled as in the case of a once through fuel cycle in Demo_Case_NFC1. The same basic units are applied: MW·a for energy, MW for power and tonne for weight. Technologies and storages which have not been described in Demo_Case_NFC1 will be introduced in the following.

Figure 3.4 presents how to construct the MOX fuel fabrication technology fuMOXLWR. One unit of MOX fuel needs 0.072 3 units of plutonium for its fabrication (see Table 3.1), as well as 0.927 7 units (= 1 − 0.072 3) of depleted uranium. The technology has two alternatives in the activity subwindow. Alternative a (alt a) uses reprocessed plutonium; whereas alternative b (alt b) uses plutonium from an external source and covers the lack of reprocessed plutonium in the system. Special attention should be paid to the signs of the values in the consa entry: all flows entering the storage need to be positive; and all the flows leaving the storage need to be negative. In this case, the flows are taken from storages and therefore have negative values.


IAEA - MESSAGE Int_V2 DEMO_CASE_NFC21 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: fuMOXLWR

activities

alt a

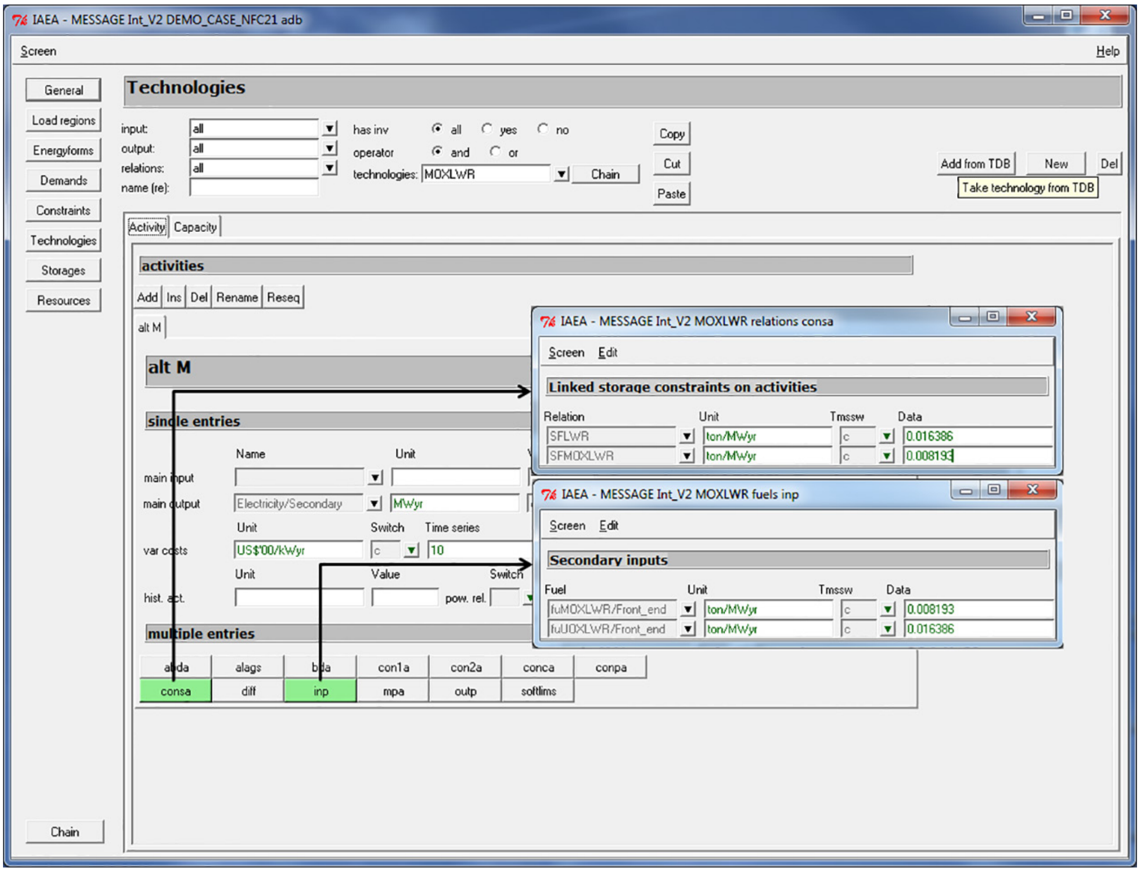
single entries

main output: Name fuMOXLWR/Front_end; Unit ton; c; 1
var costs: Unit US$'00/kg; Switch c; Time series 1200
additional options: powerchange

multiple entries

FIG. 3.4. Modelling MOX fuel fabrication technology fuMOXLWR alt a.

Reactor LWR_MOX is modelled in Figs 3.5 and 3.6. The LWR_MOX consumes annually 6.6 t HM of MOX fuel and 13.1 t HM of UOX fuel to produce 800 MW·a of electricity (see Fig. 3.2). It discharges 6.6 t of MOX spent fuel and 13.1 t of UOX spent fuel to related storages. The ratio of fresh fuel consumed by the reactor to the units of electricity output should be 0.016 4 (= 13.1/800) for UOX fuel and 0.008 19 (≈ 6.6/800) for MOX fuel (see Fig. 3.5). Fresh fuels are delivered by a secondary input. Spent nuclear fuels discharged from the reactor are also given as the ratio of the unit amount of main output 0.016 4 (= 13.1/800) for UOX spent fuel to 0.008 19 (≈ 6.6/800) for MOX spent fuel. These fuels go to the cooling storage SFLWR and SFMOXLWR.



input: all
output: all
relations: all
name (re):
technologies: MOXLWR

	Name	Unit
main input		
main output	Electricity/Secondary	MWyr

	Unit	Switch	Time series
var costs	US$'00/kWyr	c	10

	Unit	Value	Switch
hist. act.			pow. rel.

Linked storage constraints on activities

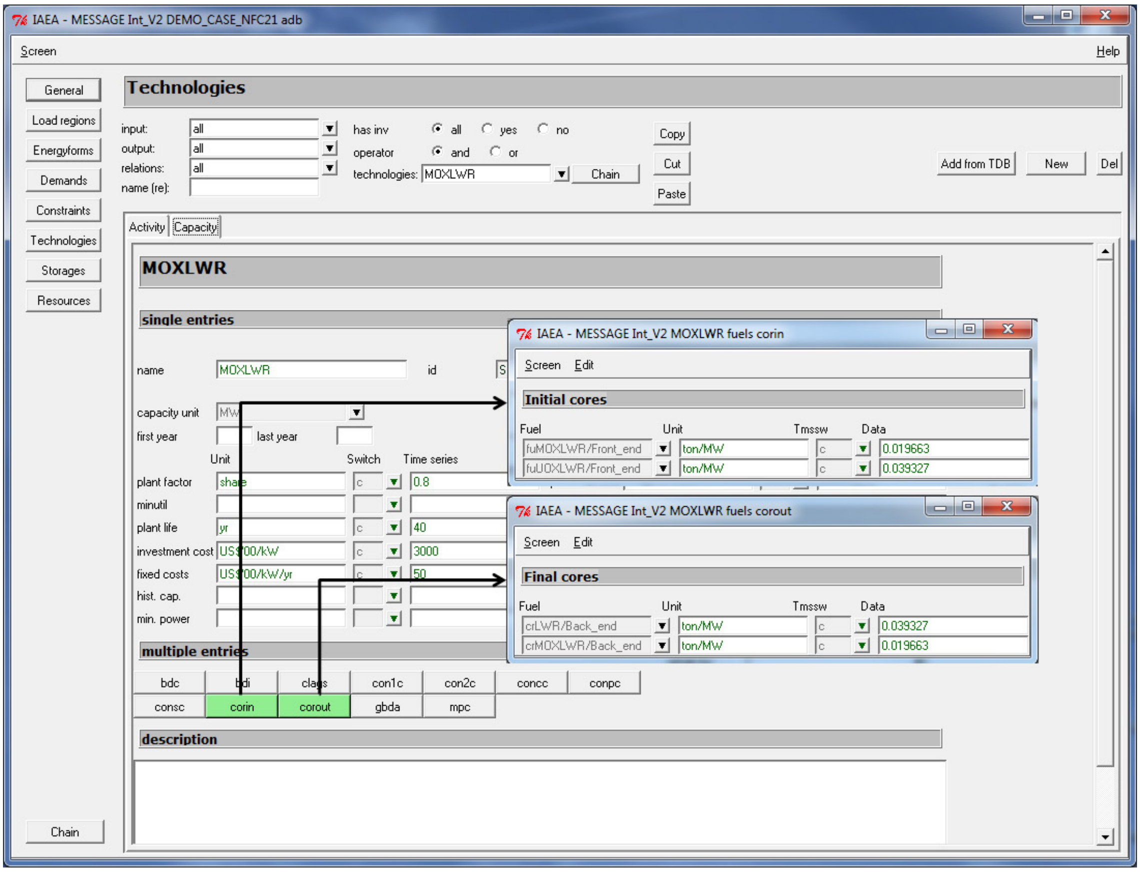
Relation	Unit	Tmssw	Data
SFLWR	ton/MWyr	c	0.016386
SFMOXLWR	ton/MWyr	c	0.008193

Secondary inputs

Fuel	Unit	Tmssw	Data
fuMOXLWR/Front_end	ton/MWyr	c	0.008193
fuUOXLWR/Front_end	ton/MWyr	c	0.016386

FIG. 3.5. *Modelling LWR_MOX reactor technology in the activity window.*

The initial core loading and final core discharge data should be given as the fraction of the unit amount of the reactor installed capacity. Two tabs labelled *corin* and *corout*, at the bottom part of *Capacity* tab in the technology window, are for the initial core loading and final core discharge, respectively (see Fig. 3.6). The LWR_MOX installed capacity is 1000 MW(e), initial core loading is 52.5 t HM for UOX fuel and 26.2 t HM for MOX fuel, annual reloading is 13.1 t HM for UOX fuel and 6.6 t HM for UOX fuel (see Table 3.5). It follows that the corresponding specific values in *corin* are 0.039 3 (≈ (52.5 − 13.1)/1000) for UOX fuel and 0.019 7 (≈ (26.2 − 6.6)/1000) for MOX fuel. The final core unloading (including fission products) is the same as first core loading, so specific values in *corout* are also 0.039 3 for UOX spent fuel and 0.019 7 for MOX spent fuel.



input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: MOXLWR

name: MOXLWR
capacity unit: MW
first year / last year

	Unit	Switch	Time series
plant factor	share	c	0.8
minutil			
plant life	yr	c	40
investment cost	US$00/kW	c	3000
fixed costs	US$00/kW/yr	c	50
hist. cap.			
min. power			

Initial cores

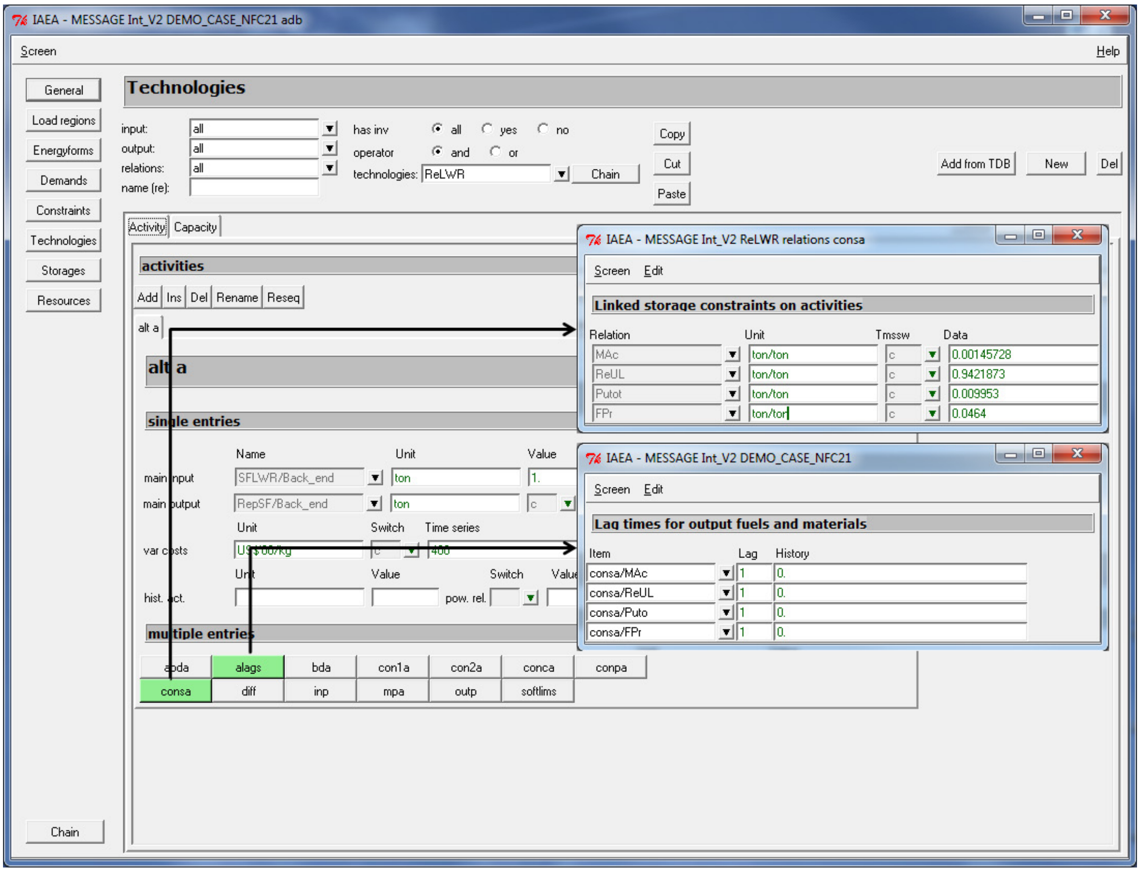
Fuel	Unit	Tmssw	Data
fuMOXLWR/Front_end	ton/MW	c	0.019663
fuUOXLWR/Front_end	ton/MW	c	0.039327

Final cores

Fuel	Unit	Tmssw	Data
crLWR/Back_end	ton/MW	c	0.039327
crMOXLWR/Back_end	ton/MW	c	0.019663

FIG. 3.6. Modelling LWR_MOX reactor technology in the capacity window.

Reprocessing technology ReLWR is constructed as a facility as shown in Figs 3.7 and 3.8. Based on the technical and economic parameters of a reprocessing facility (see Table 3.4), the activity and capacity windows are constructed. As stated earlier, only UOX fuel will be reprocessed in this case. The nuclide group composition of UOX spent fuel after five years of cooling and one year reprocessing is given in Table 3.2. It takes one unit of spent fuel and puts into storage 0.942 of uranium, 0.010 0 of plutonium, 0.001 46 of minor actinides and 0.046 4 of fission products. Input from storage should be described as a negative number. The main output has an auxiliary role, putting one unit of spent fuel to a dummy level. The lag time (one year) in the reprocessing process is entered by selecting the tab labelled *alags* in the activity window. The capacity window contains data on plant lifetime and investment cost.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC21 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: ReLWR

activities

alt a

single entries

	Name	Unit	Value
main input	SFLWR/Back_end	ton	1.
main output	RepSF/Back_end	ton	c

	Unit	Switch	Time series
var costs	US$'00/kg	c	400

	Unit	Value	pow. rel. Switch	Value
hist. act.				

multiple entries

IAEA - MESSAGE Int_V2 ReLWR relations consa

Linked storage constraints on activities

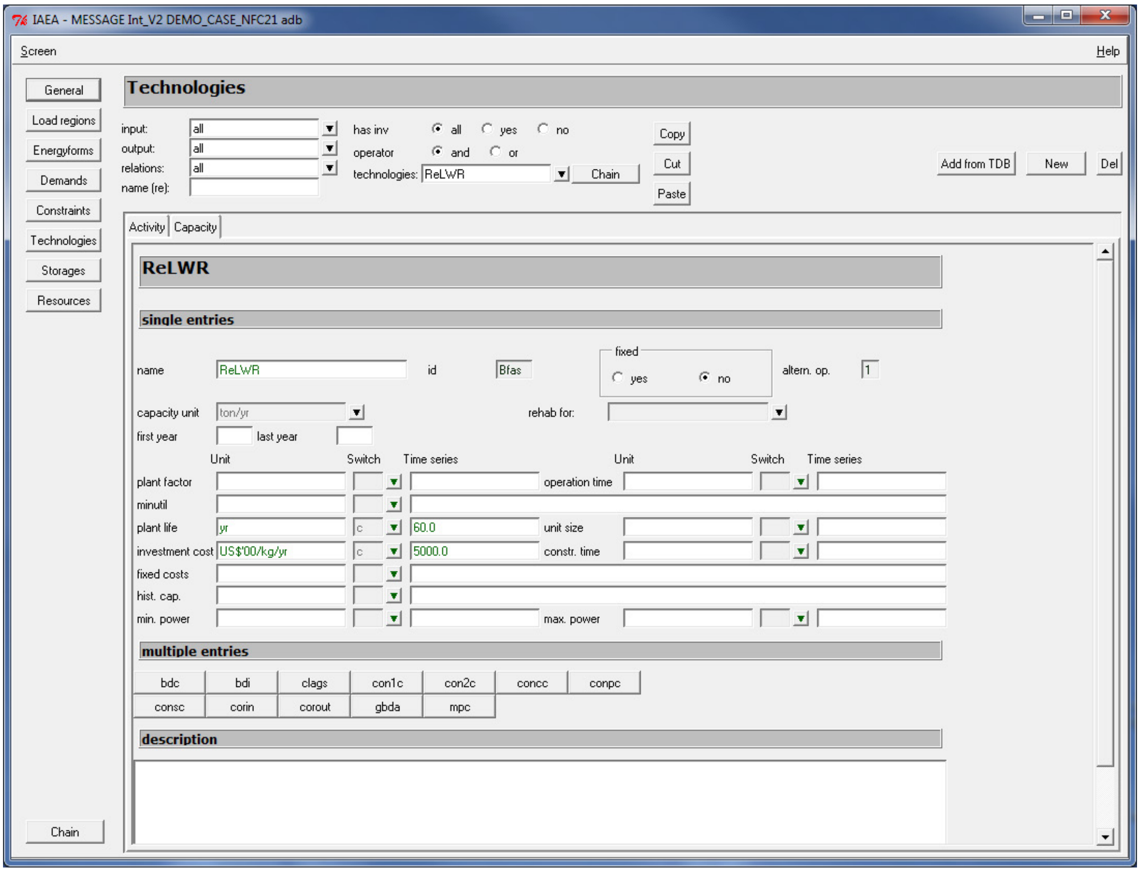
Relation	Unit	Tmssw	Data
MAc	ton/ton	c	0.00145728
ReUL	ton/ton	c	0.9421873
Putot	ton/ton	c	0.009953
FPr	ton/ton	c	0.0464

IAEA - MESSAGE Int_V2 DEMO_CASE_NFC21

Lag times for output fuels and materials

Item	Lag	History
consa/MAc	1	0.
consa/ReUL	1	0.
consa/Puto	1	0.
consa/FPr	1	0.

FIG. 3.7. Modelling reprocessing technology ReLWR in the activity window.


IAEA - MESSAGE Int_V2 DEMO_CASE_NFC21 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: ReLWR

Activity | Capacity

ReLWR

single entries

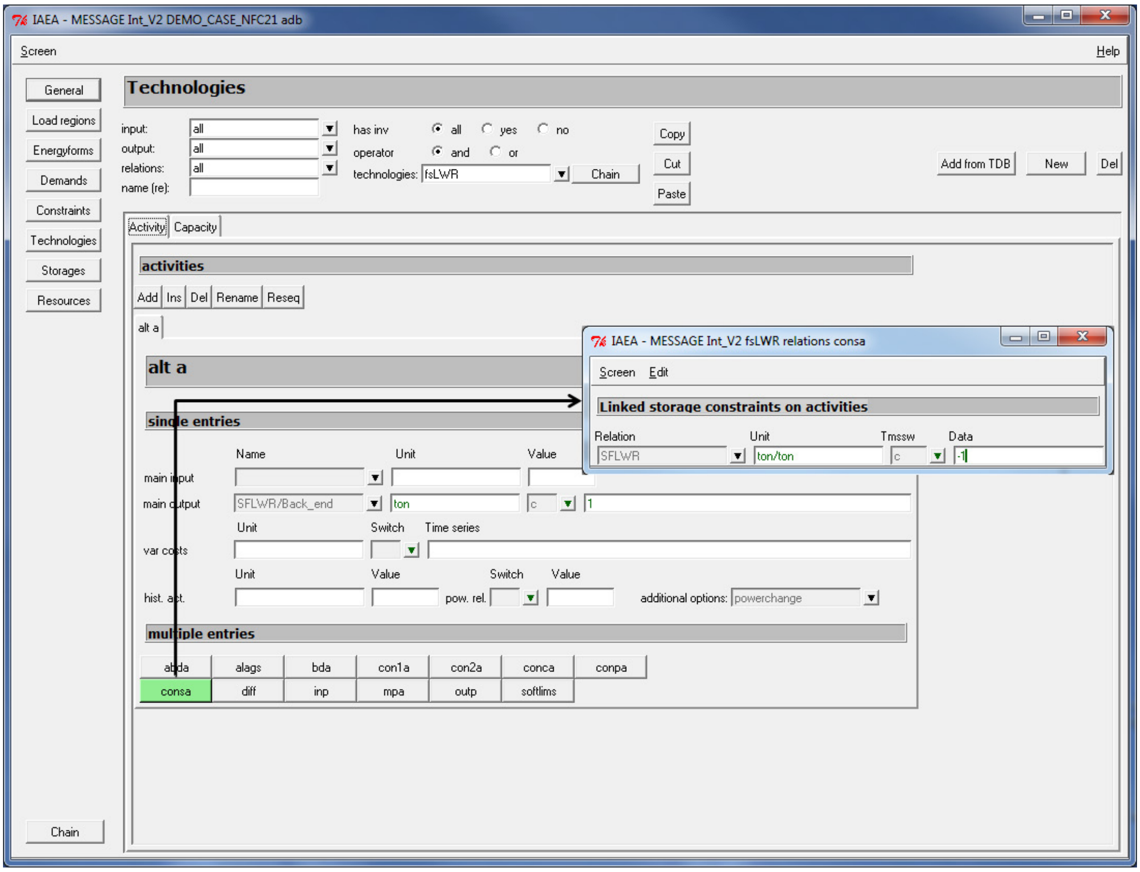
name: ReLWR
id: Bfas
fixed ○ yes ● no
altern. op.: 1
capacity unit: ton/yr
plant life: yr | c | 60.0
investment cost: US$'00/kg/yr | c | 5000.0

multiple entries

description

FIG. 3.8. Modelling reprocessing technology ReLWR in the capacity window.

Auxiliary technology fsLWR takes UOX spent fuel from UOX storage and puts it on the SFLWR energy form (see Fig. 3.9). Storages for spent fuel and depleted uranium can be modelled as in the case of the once through fuel cycle in Demo_Case_NFC1. Historical capacities for UOX fuel (13.109 t of spent fuel) annually discharged from reactor operation prior to the time period are supplied (see Fig. 3.10). Storages for reprocessed products contain only the maximum volume data and specification of entries.

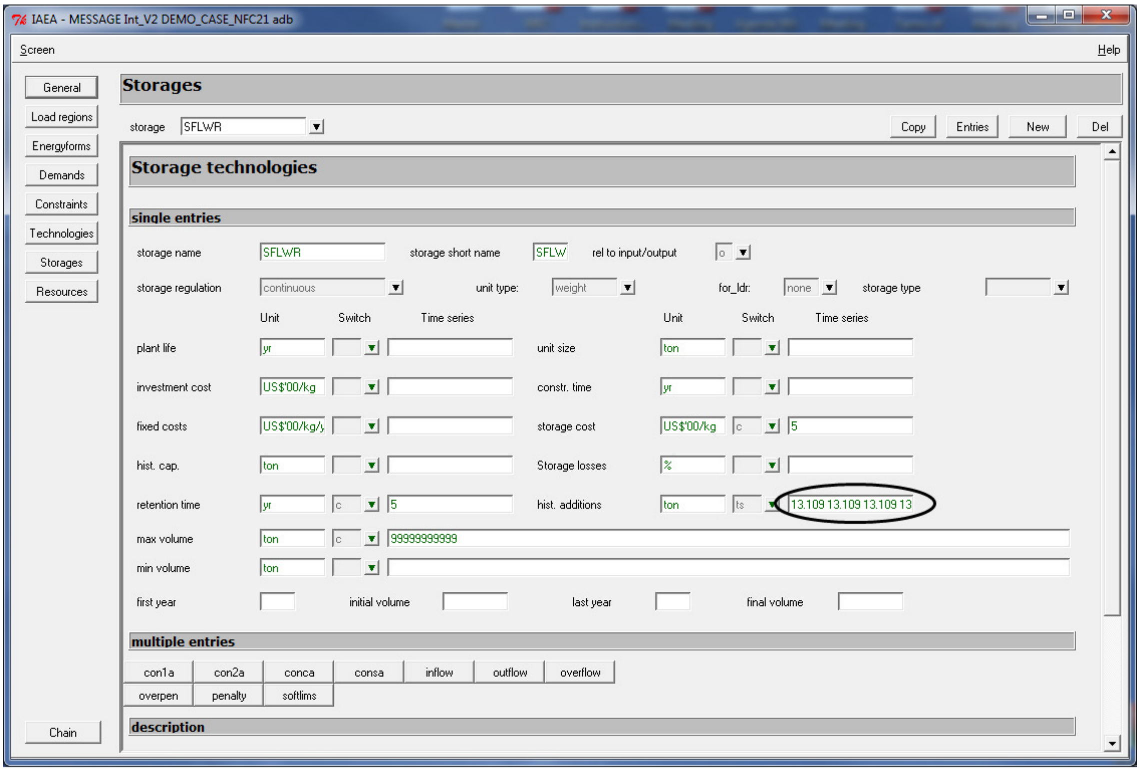


input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: fsLWR

Name | Unit | Value
main input
main output: SFLWR/Back_end, ton, c, 1
var costs — Unit, Switch, Time series
hist. act. — Unit, Value, pow. rel., Value
additional options: powerchange

Relation: SFLWR
Unit: ton/ton
Tmssw: c
Data: -1

FIG. 3.9. *Modelling auxiliary technology fsLWR.*



storage: SFLWR

storage name: SFLWR
storage short name: SFLW
rel to input/output: o
storage regulation: continuous
unit type: weight
for_ldr: none
storage type:

	Unit	Switch	Time series		Unit	Switch	Time series
plant life	yr			unit size	ton		
investment cost	US$'00/kg			constr. time	yr		
fixed costs	US$'00/kg/y			storage cost	US$'00/kg	c	5
hist. cap.	ton			Storage losses	%		
retention time	yr	c	5	hist. additions	ton	ts	13.109 13.109 13.109 13
max volume	ton	c	99999999999				
min volume	ton						

first year:
initial volume:
last year:
final volume:

FIG. 3.10. Modelling storages.

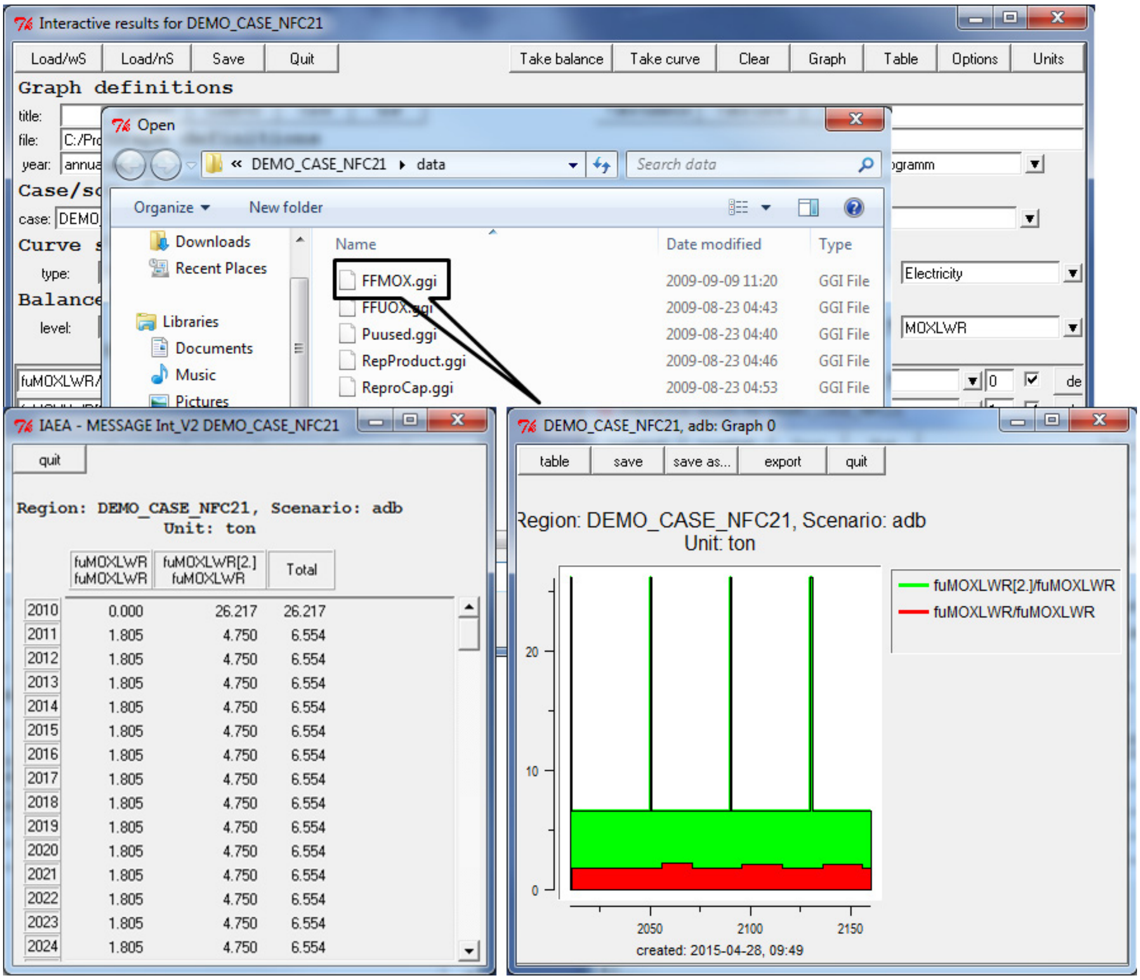
3.1.3. Mass flow MESSAGE outputs for a partially closed fuel cycle with one unit of an LWR_MOX without the recycling of reprocessed uranium

In order to validate the results of the model, the interactive mode of MESSAGE will be used again. After running MESSAGE Demo_Case_NFC2, the mass flow result can be displayed in the interactive mode and compared with analytical calculations (see Table 3.5 and Fig. 3.2). The selected and saved results are in Table 3.7. Results can be reloaded using the tab labelled *Load/ws*.

TABLE 3.7. SELECTED MASS FLOW OUTPUTS FOR A PARTIALLY CLOSED FUEL CYCLE WITHOUT THE RECYCLING OF REPROCESSED URANIUM

File name of results, selected and saved	Explanation
FFMOX.ggi	MOX fresh fuel requirements
FFUOX.ggi	UOX fresh fuel requirements
Puused.ggi	Plutonium used for MOX fuel fabrication
RepProduct.ggi	Reprocessed products (plutonium, minor actinides, uranium and fission products)
ReproCap.ggi	Reprocessing capacity and requirement

MOX fuel requirements can be extracted by selecting the output of technology fuMOXLWR (see Fig. 3.11). The result in the table is 6.6 t HM of annual MOX fuel requirements. 1.8 t HM of MOX fuel are fabricated from 0.13 t HM of reprocessed plutonium. Of MOX fuel, 4.8 t HM of MOX fuel are fabricated from 0.343 t HM of external plutonium sources. Analytical calculations yield the same result.

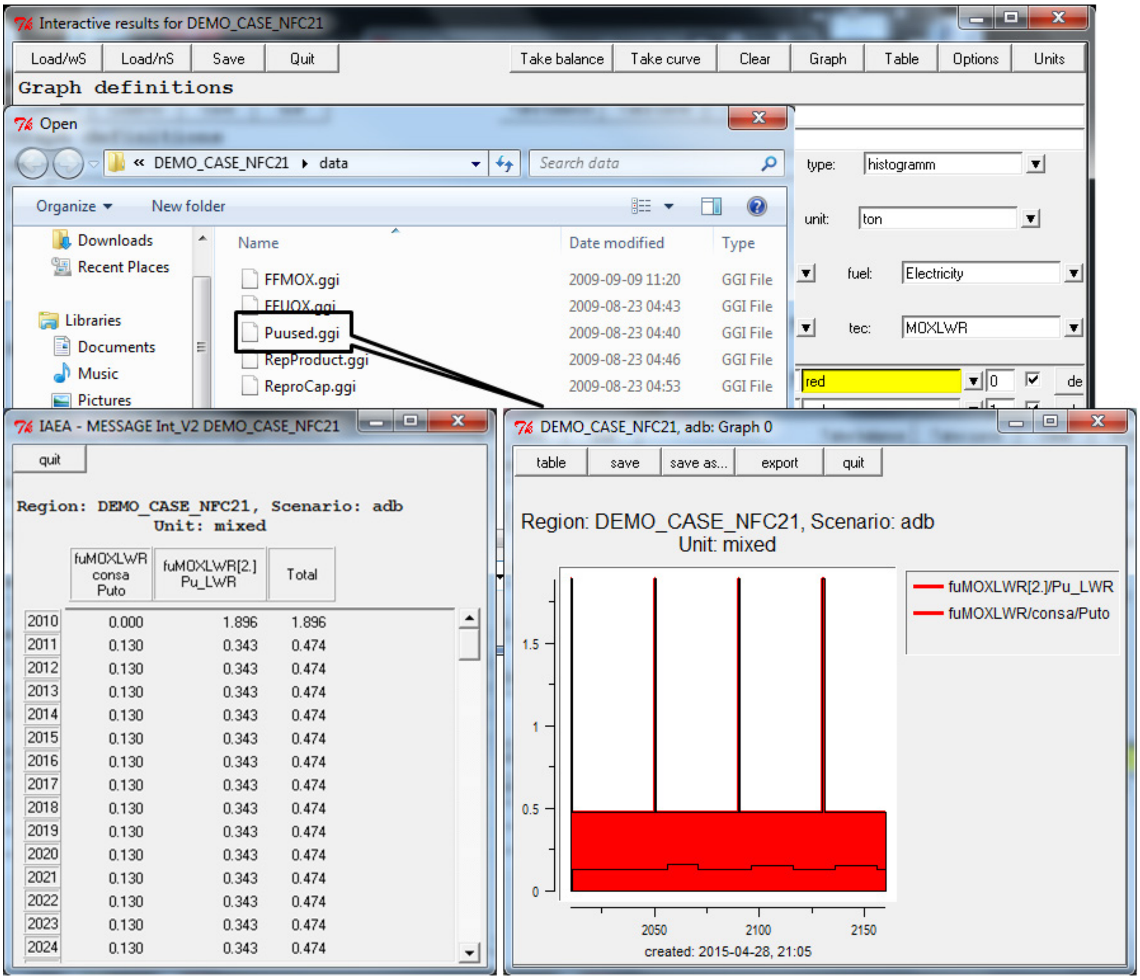


Region: DEMO_CASE_NFC21, Scenario: adb
Unit: ton

	fuMOXLWR fuMOXLWR	fuMOXLWR[2.] fuMOXLWR	Total
2010	0.000	26.217	26.217
2011	1.805	4.750	6.554
2012	1.805	4.750	6.554
2013	1.805	4.750	6.554
2014	1.805	4.750	6.554
2015	1.805	4.750	6.554
2016	1.805	4.750	6.554
2017	1.805	4.750	6.554
2018	1.805	4.750	6.554
2019	1.805	4.750	6.554
2020	1.805	4.750	6.554
2021	1.805	4.750	6.554
2022	1.805	4.750	6.554
2023	1.805	4.750	6.554
2024	1.805	4.750	6.554

FIG. 3.11. MOX fresh fuel requirements.

The required plutonium can be extracted from the consa aspect and the secondary input of technology fuMOXLWR (see Fig. 3.12). UOX fuel requirements (13.1 t HM of fresh UOX fuel) are shown in Fig. 3.13, as extracted from main input of fuUOXLWR technology. Results for reprocessed products are given in Fig. 3.14. They are extracted from the consa aspect of reprocessing technology ReLWR and respectively equal 12.35 t HM of uranium, 0.130 t HM of plutonium, 0.019 t HM of minor actinides and 0.608 t of fission products. These results are consistent with analytical calculations.



Name	Date modified	Type
FFMOX.ggi	2009-09-09 11:20	GGI File
FFUOX.ggi	2009-08-23 04:43	GGI File
Puused.ggi	2009-08-23 04:40	GGI File
RepProduct.ggi	2009-08-23 04:46	GGI File
ReproCap.ggi	2009-08-23 04:53	GGI File

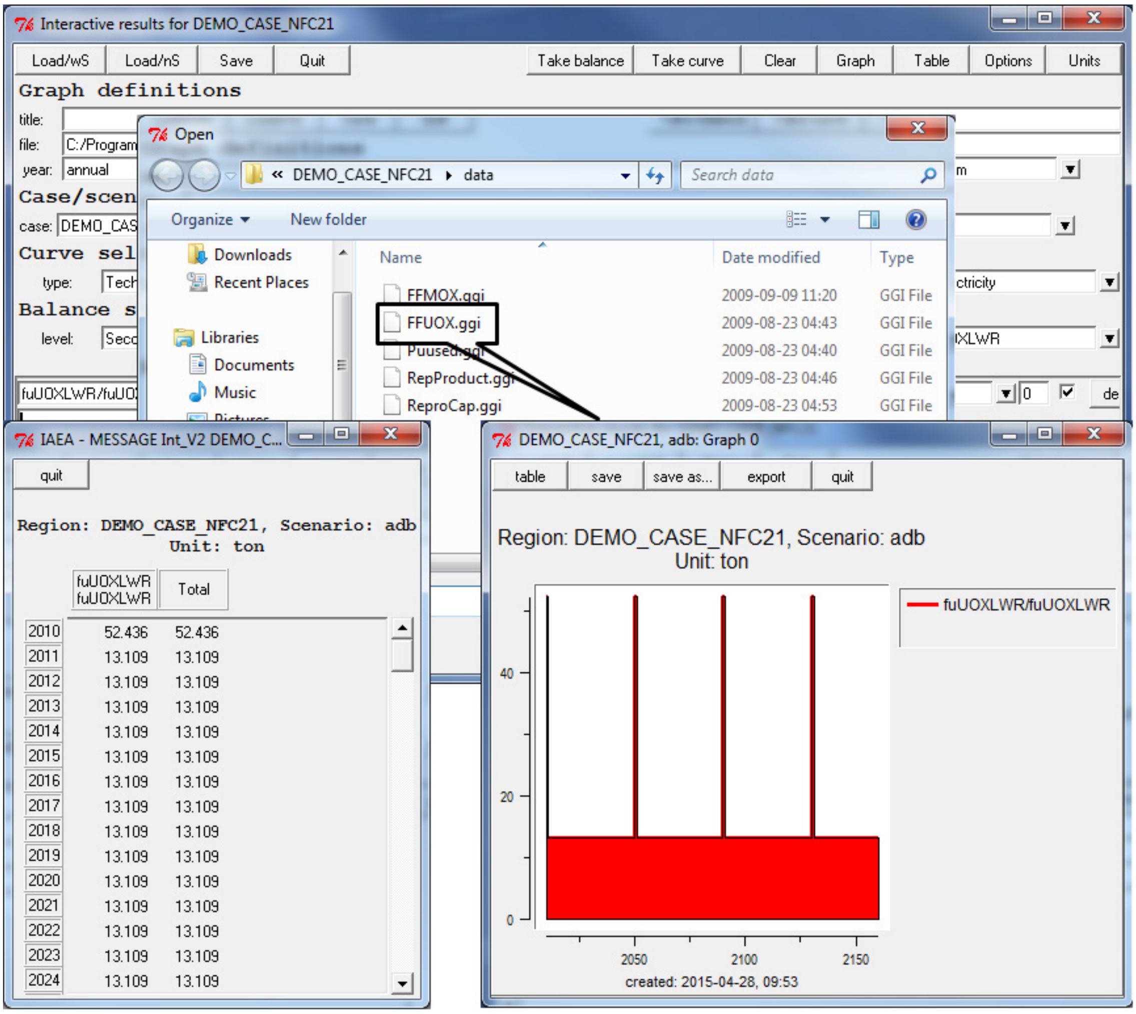
type: histogramm
unit: ton
fuel: Electricity
tec: MOXLWR
red 0 ☑

```
Region: DEMO_CASE_NFC21, Scenario: adb
                 Unit: mixed

        fuMOXLWR   fuMOXLWR[2.]   Total
          consa      Pu_LWR
          Puto
2010      0.000       1.896       1.896
2011      0.130       0.343       0.474
2012      0.130       0.343       0.474
2013      0.130       0.343       0.474
2014      0.130       0.343       0.474
2015      0.130       0.343       0.474
2016      0.130       0.343       0.474
2017      0.130       0.343       0.474
2018      0.130       0.343       0.474
2019      0.130       0.343       0.474
2020      0.130       0.343       0.474
2021      0.130       0.343       0.474
2022      0.130       0.343       0.474
2023      0.130       0.343       0.474
2024      0.130       0.343       0.474
```

Region: DEMO_CASE_NFC21, Scenario: adb
Unit: mixed

FIG. 3.12. Plutonium used for MOX fuel fabrication.



file: C:/Program

year: annual

case: DEMO_CAS

type: Tech

level: Seco

fuUOXLWR/fuUO

Name	Date modified	Type
FFMOX.ggi	2009-09-09 11:20	GGI File
FFUOX.ggi	2009-08-23 04:43	GGI File
Puused.ggi	2009-08-23 04:40	GGI File
RepProduct.ggi	2009-08-23 04:46	GGI File
ReproCap.ggi	2009-08-23 04:53	GGI File

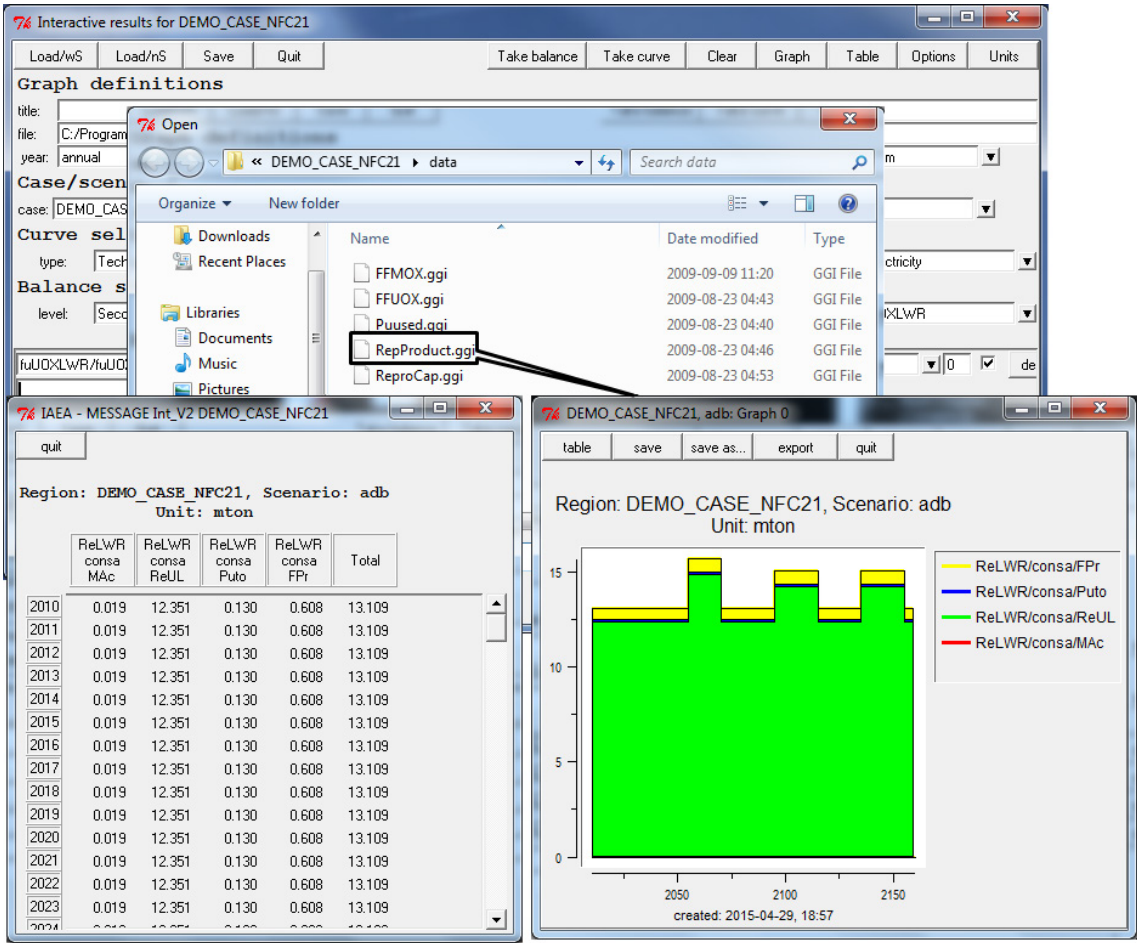
Region: DEMO_CASE_NFC21, Scenario: adb
Unit: ton

	fuUOXLWR fuUOXLWR	Total
2010	52.436	52.436
2011	13.109	13.109
2012	13.109	13.109
2013	13.109	13.109
2014	13.109	13.109
2015	13.109	13.109
2016	13.109	13.109
2017	13.109	13.109
2018	13.109	13.109
2019	13.109	13.109
2020	13.109	13.109
2021	13.109	13.109
2022	13.109	13.109
2023	13.109	13.109
2024	13.109	13.109

Region: DEMO_CASE_NFC21, Scenario: adb
Unit: ton

created: 2015-04-28, 09:53

FIG. 3.13. UOX fresh fuel requirements.



title:
file: C:/Program
year: annual
case: DEMO_CAS
type: Tech
level: Seco
fuUOXLWR/fuUO
m
ctricity
XLWR
0
☑
de

Name	Date modified	Type
FFMOX.ggi	2009-09-09 11:20	GGI File
FFUOX.ggi	2009-08-23 04:43	GGI File
Puused.ggi	2009-08-23 04:40	GGI File
RepProduct.ggi	2009-08-23 04:46	GGI File
ReproCap.ggi	2009-08-23 04:53	GGI File

Region: DEMO_CASE_NFC21, Scenario: adb
Unit: mton

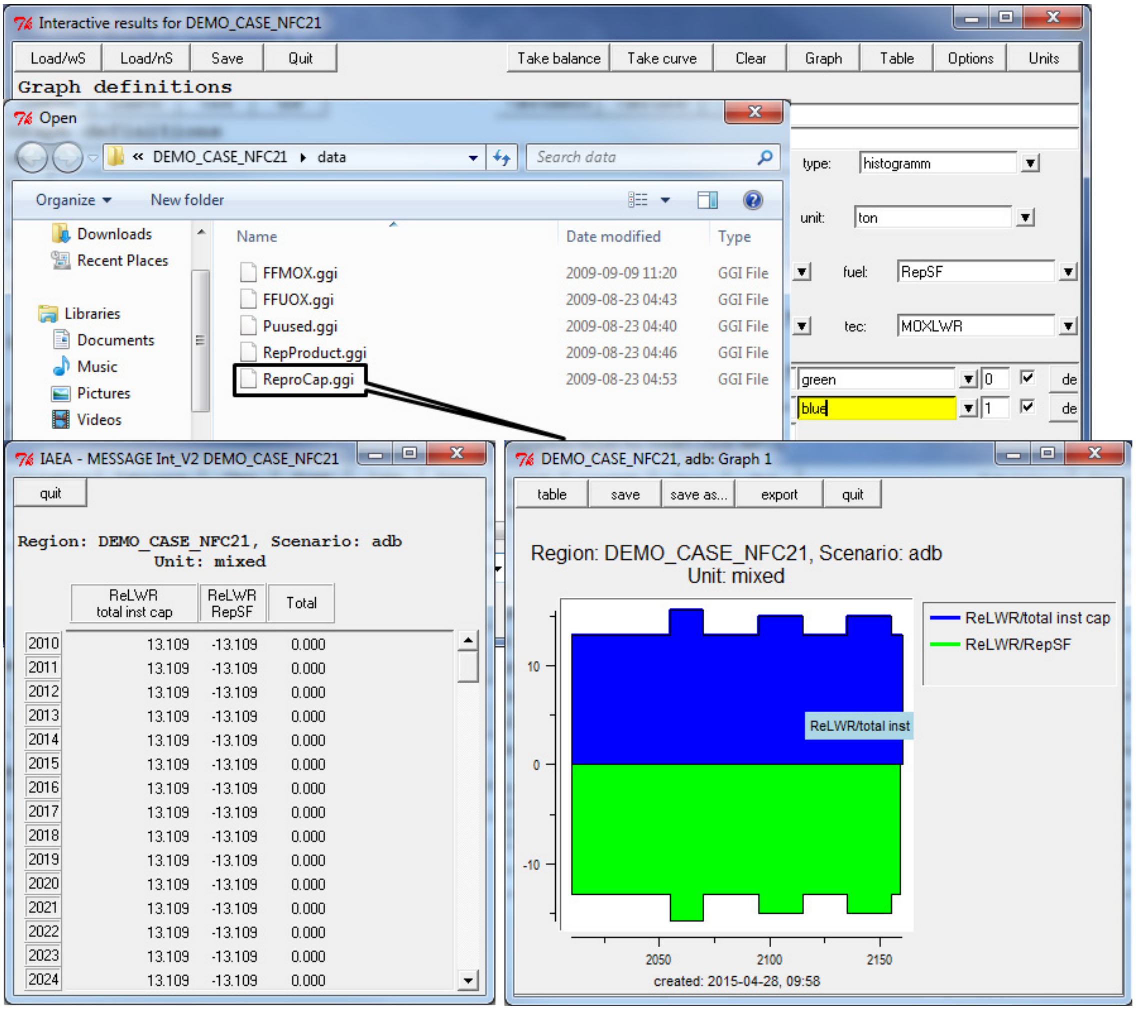
	ReLWR consa MAc	ReLWR consa ReUL	ReLWR consa Puto	ReLWR consa FPr	Total
2010	0.019	12.351	0.130	0.608	13.109
2011	0.019	12.351	0.130	0.608	13.109
2012	0.019	12.351	0.130	0.608	13.109
2013	0.019	12.351	0.130	0.608	13.109
2014	0.019	12.351	0.130	0.608	13.109
2015	0.019	12.351	0.130	0.608	13.109
2016	0.019	12.351	0.130	0.608	13.109
2017	0.019	12.351	0.130	0.608	13.109
2018	0.019	12.351	0.130	0.608	13.109
2019	0.019	12.351	0.130	0.608	13.109
2020	0.019	12.351	0.130	0.608	13.109
2021	0.019	12.351	0.130	0.608	13.109
2022	0.019	12.351	0.130	0.608	13.109
2023	0.019	12.351	0.130	0.608	13.109

Region: DEMO_CASE_NFC21, Scenario: adb
Unit: mton

created: 2015-04-29, 18:57

FIG. 3.14. *Reprocessed products (plutonium, minor actinides, uranium and fission products).*

Reprocessing is modelled as a facility with a capacity factor of 100%. The installed capacities of reprocessing are in line with the previous spent fuel reprocessing requirement, as the installed capacity is equal to the reprocessing requirement. After 2055, new reprocessing capacities are installed to reprocess spent fuel discharged from the whole core after reactor shutdown (see Fig. 3.15).



type: histogramm

unit: ton

fuel: RepSF

tec: MOXLWR

green 0 ☑

blue 1 ☑

Name	Date modified	Type
FFMOX.ggi	2009-09-09 11:20	GGI File
FFUOX.ggi	2009-08-23 04:43	GGI File
Puused.ggi	2009-08-23 04:40	GGI File
RepProduct.ggi	2009-08-23 04:46	GGI File
ReproCap.ggi	2009-08-23 04:53	GGI File

Region: DEMO_CASE_NFC21, Scenario: adb
Unit: mixed

	ReLWR total inst cap	ReLWR RepSF	Total
2010	13.109	-13.109	0.000
2011	13.109	-13.109	0.000
2012	13.109	-13.109	0.000
2013	13.109	-13.109	0.000
2014	13.109	-13.109	0.000
2015	13.109	-13.109	0.000
2016	13.109	-13.109	0.000
2017	13.109	-13.109	0.000
2018	13.109	-13.109	0.000
2019	13.109	-13.109	0.000
2020	13.109	-13.109	0.000
2021	13.109	-13.109	0.000
2022	13.109	-13.109	0.000
2023	13.109	-13.109	0.000
2024	13.109	-13.109	0.000

Region: DEMO_CASE_NFC21, Scenario: adb
Unit: mixed

created: 2015-04-28, 09:58

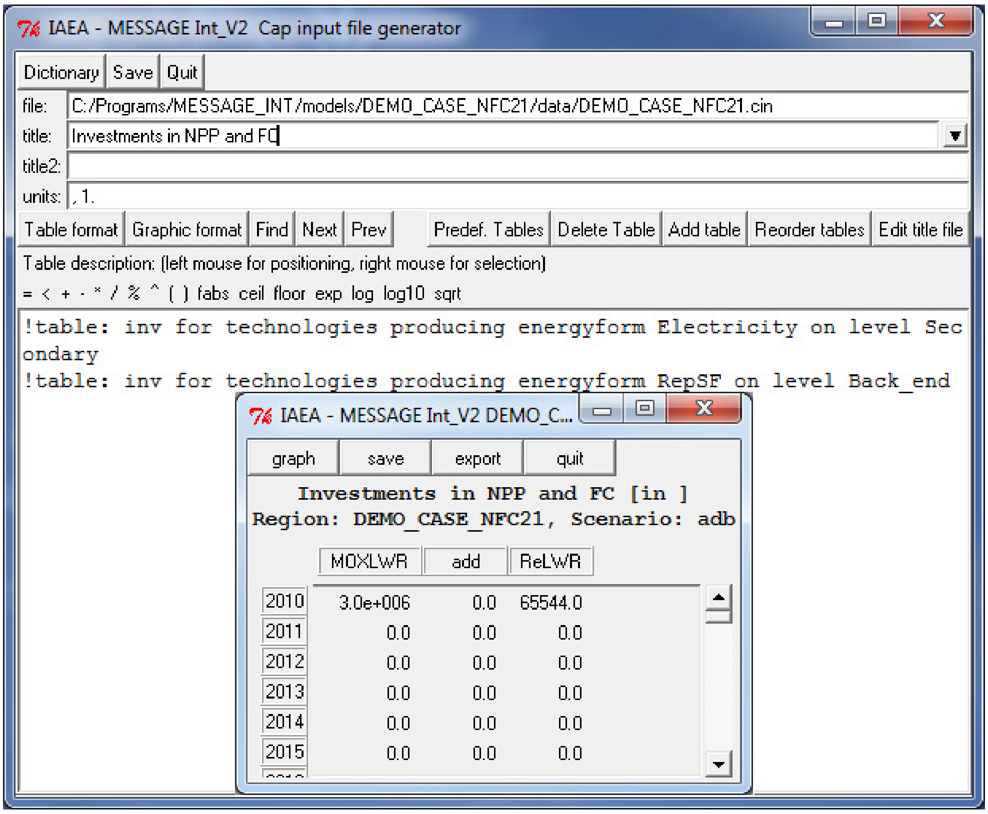
FIG. 3.15. *Reprocessing capacity and requirement.*

3.1.4. Economic results of MESSAGE modelling for a partially closed fuel cycle with one unit of an LWR_MOX without the recycling of reprocessed uranium

The economic results are extracted through a cin file, prepared in the same way as in Demo_Case_NFC1. Three tables were prepared to calculate the following results:

- Annual investments in the NPP;
- Annual expenditure on the total fuel cycle and O&M of the NPP;
- LUAC&LUOM.

Annual investments in the NPP are given in Fig. 3.16, as prepared with predefined tables, selecting the tab labelled *Predef. Tables*. Investment costs for technologies producing energy form electricity at the secondary level were selected. Investments and other costs are measured in thousands of US dollars, since the unit of capacity is MW and overnight cost has the unit US $/kW (MW × US $/kW = US $1000). The result for annual investment in LWR_MOX is US $3 billion in 2009 (= 3 × 10^6 × US $1000), given in the table in Fig. 3.16.



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC21/data/DEMO_CASE_NFC21.cin
title: Investments in NPP and FC
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)
= < + - * / % ^ ( ) fabs ceil floor exp log log10 sqrt

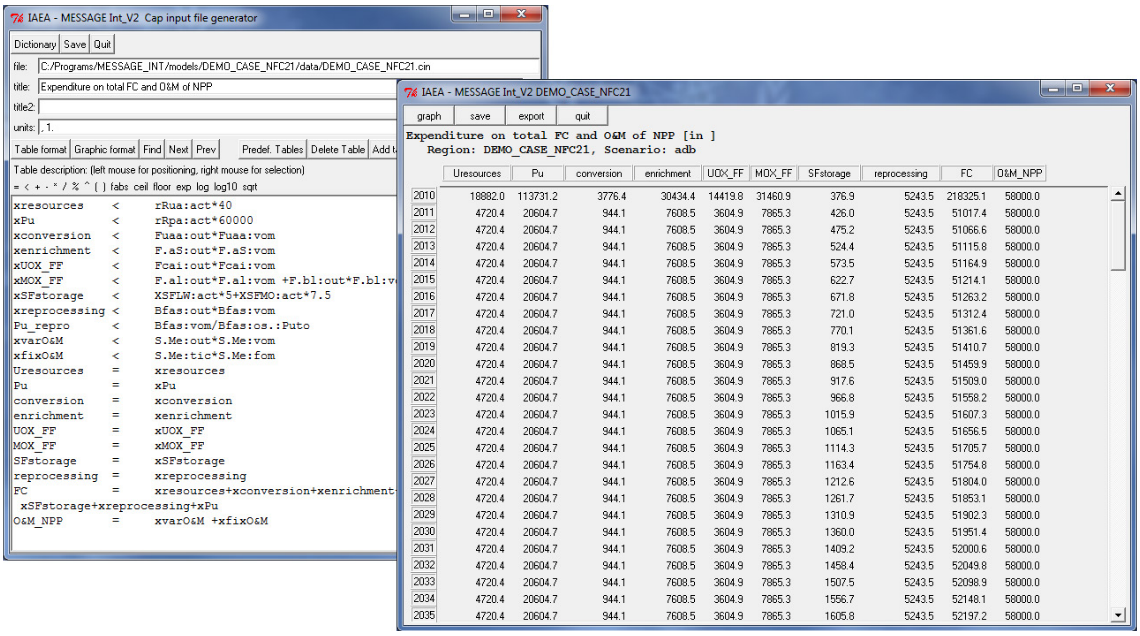
```
!table: inv for technologies producing energyform Electricity on level Sec
ondary
!table: inv for technologies producing energyform RepSF on level Back_end
```

```
    Investments in NPP and FC [in ]
Region: DEMO_CASE_NFC21, Scenario: adb

         MOXLWR     add     ReLWR
2010    3.0e+006    0.0   65544.0
2011         0.0    0.0       0.0
2012         0.0    0.0       0.0
2013         0.0    0.0       0.0
2014         0.0    0.0       0.0
2015         0.0    0.0       0.0
```

FIG. 3.16. *Annual investments in the NPP.*

Annual expenditure on the fuel cycle and O&M of the NPP is given in Fig. 3.17. The expenditure on the fuel cycle includes calculations for resources, conversion, enrichment, UOX and MOX fresh fuel fabrication, reprocessing and spent fuel storage. Expenditure on a given fuel cycle step is obtained by multiplying a material amount for a given step by the corresponding specific cost. The data calculated are given on the right of Fig. 3.17. Annual expenditure on O&M of the NPP (fixed and variable O&M) was also included. Costs and investment are measured in thousands of US dollars. LUAC&LUOM for an LWR — US $261.96/kW·a — was prepared with predefined tables.



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC21/data/DEMO_CASE_NFC21.cin
title: Expenditure on total FC and O&M of NPP
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)

```
xresources    <     rRua:act*40
xPu           <     rRpa:act*60000
xconversion   <     Fuaa:out*Fuaa:vom
xenrichment   <     F.aS:out*F.aS:vom
xUOX_FF       <     Fcai:out*Fcai:vom
xMOX_FF       <     F.al:out*F.al:vom +F.bl:out*F.bl:v
xSFstorage    <     XSFLW:act*5+XSFMO:act*7.5
xreprocessing <     Bfas:out*Bfas:vom
Pu_repro      <     Bfas:vom/Bfas:os.:Puto
xvarO&M       <     S.Me:out*S.Me:vom
xfixO&M       <     S.Me:tic*S.Me:fom
Uresources    =     xresources
Pu            =     xPu
conversion    =     xconversion
enrichment    =     xenrichment
UOX_FF        =     xUOX_FF
MOX_FF        =     xMOX_FF
SFstorage     =     xSFstorage
reprocessing  =     xreprocessing
FC            =     xresources+xconversion+xenrichment
 xSFstorage+xreprocessing+xPu
O&M_NPP       =     xvarO&M +xfixO&M
```

Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC21, Scenario: adb

	Uresources	Pu	conversion	enrichment	UOX_FF	MOX_FF	SFstorage	reprocessing	FC	O&M_NPP
2010	18882.0	113731.2	3776.4	30434.4	14419.8	31460.9	376.9	5243.5	218325.1	58000.0
2011	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	426.0	5243.5	51017.4	58000.0
2012	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	475.2	5243.5	51066.6	58000.0
2013	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	524.4	5243.5	51115.8	58000.0
2014	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	573.5	5243.5	51164.9	58000.0
2015	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	622.7	5243.5	51214.1	58000.0
2016	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	671.8	5243.5	51263.2	58000.0
2017	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	721.0	5243.5	51312.4	58000.0
2018	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	770.1	5243.5	51361.6	58000.0
2019	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	819.3	5243.5	51410.7	58000.0
2020	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	868.5	5243.5	51459.9	58000.0
2021	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	917.6	5243.5	51509.0	58000.0
2022	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	966.8	5243.5	51558.2	58000.0
2023	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1015.9	5243.5	51607.3	58000.0
2024	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1065.1	5243.5	51656.5	58000.0
2025	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1114.3	5243.5	51705.7	58000.0
2026	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1163.4	5243.5	51754.8	58000.0
2027	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1212.6	5243.5	51804.0	58000.0
2028	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1261.7	5243.5	51853.1	58000.0
2029	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1310.9	5243.5	51902.3	58000.0
2030	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1360.0	5243.5	51951.4	58000.0
2031	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1409.2	5243.5	52000.6	58000.0
2032	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1458.4	5243.5	52049.8	58000.0
2033	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1507.5	5243.5	52098.9	58000.0
2034	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1556.7	5243.5	52148.1	58000.0
2035	4720.4	20604.7	944.1	7608.5	3604.9	7865.3	1605.8	5243.5	52197.2	58000.0

FIG. 3.17. Annual expenditure on the fuel cycle and O&M of the NPP.

3.2. A PARTIALLY CLOSED FUEL CYCLE WITH ONE UNIT OF AN LWR_MOX WITH THE RECYCLING OF REPROCESSED URANIUM

Recovered uranium from a reprocessing plant may be enriched again for reuse as fresh fuel. Because it contains some impurities (e.g. neutron absorbing ^{236}U), reprocessed uranium needs to be more enriched than is required for natural uranium. One simple way to compensate the neutron absorption by ^{236}U is to replace value of uranium enrichment Enr by (Enr + U236SF) for enrichment from reprocessed uranium. Reprocessing of 13.1 t of UOX used fuel produces 12.4 t HM of reprocessed uranium (RepU) (see Eqs (3.16) and (3.17)). Equation (3.18) provides that 12.4 t HM of reprocessed uranium is enriched again to 1.45 t HM of UOX fresh fuel, with a consumption of 8.29 t SWU (see Eq. (3.19)) and the production of 11 t HM of depleted uranium (see Eq. (3.20)):

(a) Conversion of reprocessed uranium:

$$\text{Cnrep} = \text{RepU} \tag{3.17}$$

(b) Annual UOX fresh fuel loading from reprocessed uranium:

$$\text{FFUOXrep} = \frac{\text{RepU}}{\text{Enr} - \text{Ta} \big/ 0.007114 - \text{Ta}} \tag{3.18}$$

where 0.007 114 is the content of ^{235}U in natural uranium

(c) Separative work for fresh fuel from reprocessed uranium:

$$\text{SWUrep} = \text{FFUOXrep} \times \left(V(\text{Enr} + \text{U236SF}) + V(\text{Ta}) \frac{\text{Enr} + \text{U236SF} - \text{U235SF}}{\text{U235SF} - \text{Ta}} - V(\text{U235SF}) \frac{\text{Enr} + \text{U236SF} - \text{Ta}}{\text{U235SF} - \text{Ta}} \right) \tag{3.19}$$

where U235SF is the content of ^{235}U in reprocessed uranium and U2365SF is the content of ^{236}U in reprocessed uranium

(d) Depleted uranium production for fresh fuel from reprocessed uranium:

$$\text{DepUrep} = \text{FFUOXrep} \times \frac{\text{Enr} + \text{U236SF} - \text{U235SF}}{\text{U235SF} - \text{Ta}} \tag{3.20}$$

(e) The requirement for fresh fuel from natural uranium will be decreased to 11.65 t HM (see Eq. (3.21)). Thus, to obtain 11.65 t HM of enriched uranium, an input of 105 t HM (see Eq. (3.22)) of converted uranium is needed, as well as 61.5 t SWU (see Eq. (3.23)) and 93 t HM of depleted uranium (see Eq. (3.20)) (see also Fig. 3.18). Annual fresh fuel loading from natural uranium:

$$\text{FFUOXnat} = \frac{2}{3} \times \frac{365 \times \text{NC} \times \text{Lf}}{\text{Eff} \times \text{Bu}} - \text{FFUOXrep} \tag{3.21}$$

(f) Depleted uranium production for fresh fuel from natural uranium:

$$\text{DepUnat} = \text{FFUOXnat} \times \frac{\text{Enr} - 0.007114}{0.007114 - \text{Ta}} \tag{3.22}$$

(g) Separative work for fresh fuel from natural uranium:

$$\text{SWUrnat} = \text{FFUOXnat} \times \left(V(\text{Enr}) + V(\text{Ta}) \frac{\text{Enr} - 0.007114}{0.007114 - \text{Ta}} - V(0.007114) \frac{\text{Enr} - \text{Ta}}{0.007114 - \text{Ta}} \right) \tag{3.23}$$

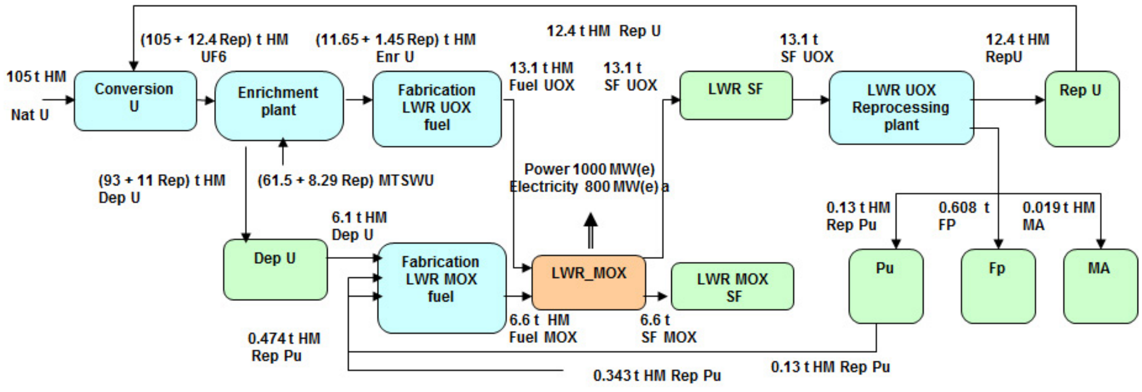
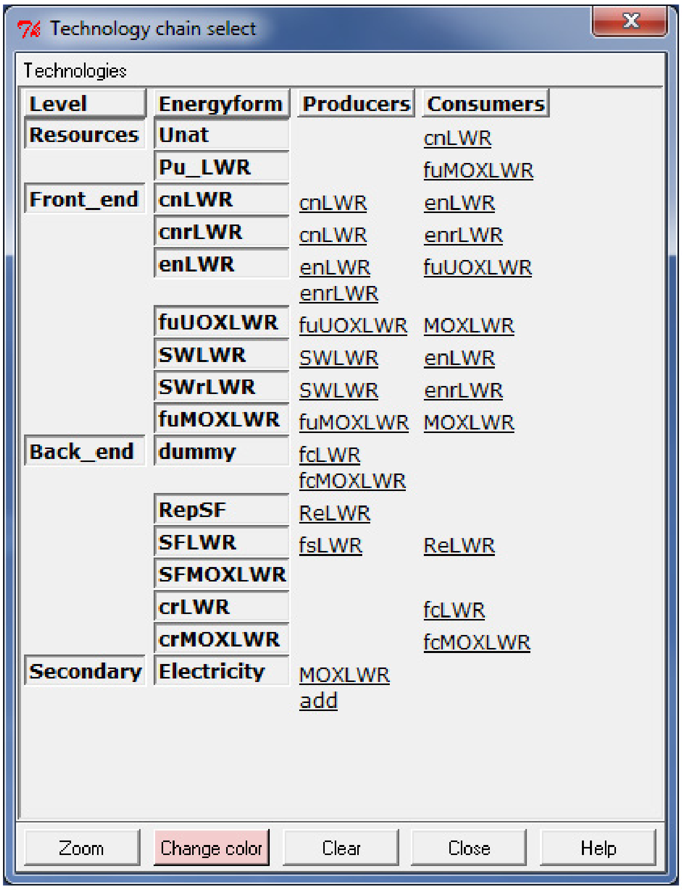


FIG. 3.18. *Mass balance of the LWR_MOX fuel cycle with uranium recycling.*

Impurities in reprocessed uranium — such as ^{232}U, whose decay products emit strong gamma radiation — make it more difficult than natural uranium to handle and use. Because of the difficulty of handling the more radioactive reprocessed uranium, the enrichment cost is anticipated to be higher than for virgin enrichment plant feed. Thus, a 20–30% penalty on the price of SWU is warranted. A fabrication plant needs to minimize personnel radiation exposure by using additional automated systems to handle the process steps, and additional shielding may be required. For these reasons, the cost of reprocessed UOX fuel fabrication is expected to be at least several per cent higher than for virgin enriched fuel.

3.2.1. MESSAGE modelling of a partially closed fuel cycle with one unit of an LWR_MOX with the recycling of reprocessed uranium (Demo_Case_NFC22)

The MESSAGE energy and technology chain of a partially closed fuel cycle option with LWR_MOX and uranium recycling is shown in Fig. 3.19. Some additional energy forms and technologies, or technology alternatives, should be added to the previous model for the re-enrichment of reprocessed uranium (see Table 3.8).



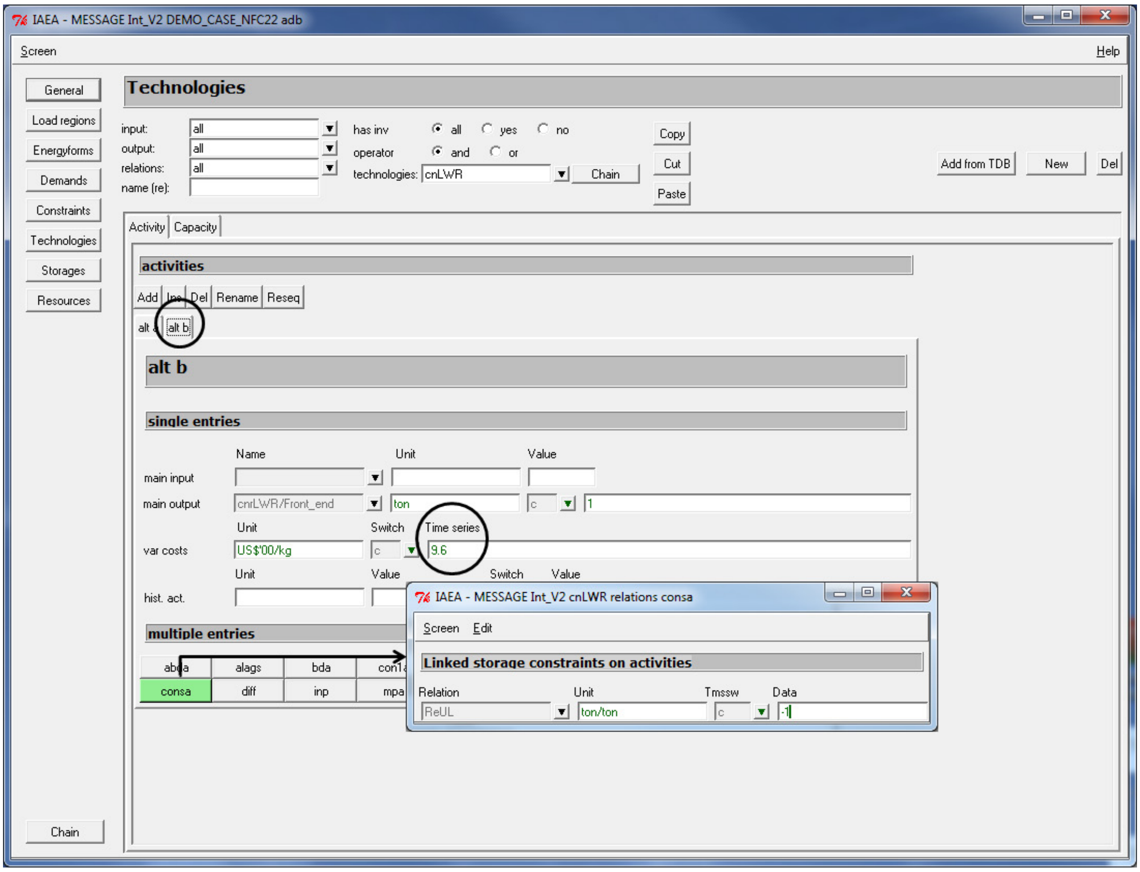
Level	Energyform	Producers	Consumers
Resources	Unat		cnLWR
	Pu_LWR		fuMOXLWR
Front_end	cnLWR	cnLWR	enLWR
	cnrLWR	cnLWR	enrLWR
	enLWR	enLWR enrLWR	fuUOXLWR
	fuUOXLWR	fuUOXLWR	MOXLWR
	SWLWR	SWLWR	enLWR
	SWrLWR	SWLWR	enrLWR
	fuMOXLWR	fuMOXLWR	MOXLWR
Back_end	dummy	fcLWR fcMOXLWR	
	RepSF	ReLWR	
	SFLWR	fsLWR	ReLWR
	SFMOXLWR		
	crLWR		fcLWR
	crMOXLWR		fcMOXLWR
Secondary	Electricity	MOXLWR add	

FIG. 3.19. Technology chain.

TABLE 3.8. TECHNOLOGIES FOR THE RE-ENRICHMENT OF REPROCESSED URANIUM

Technology	Explanation
cnLWR alt b	Conversion of reprocessed uranium to uranium hexafluoride (UF_6)
enrLWR and SWLWR alt b	Enrichment of reprocessed uranium

The alt b is added to conversion technology cnLWR for conversion of reprocessed uranium. To obtain one unit of converted uranium, one unit of reprocessed uranium needs to be taken out from the uranium storage ReUL (see Fig. 3.20). Additional costs are to be paid for the conversion reprocessed uranium service compared to the conversion of natural uranium.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC22 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv: ● all ○ yes ○ no
operator: ● and ○ or
technologies: cnLWR

activities

alt b

single entries

	Name	Unit	Switch	Value
main input				
main output	cnrLWR/Front_end	ton	c	1

	Unit	Switch	Time series
var costs	US$'00/kg	c	9.6

	Unit	Value	Switch	Value
hist. act.				

multiple entries

abda	alags	bda	con1a
consa	diff	inp	mpa

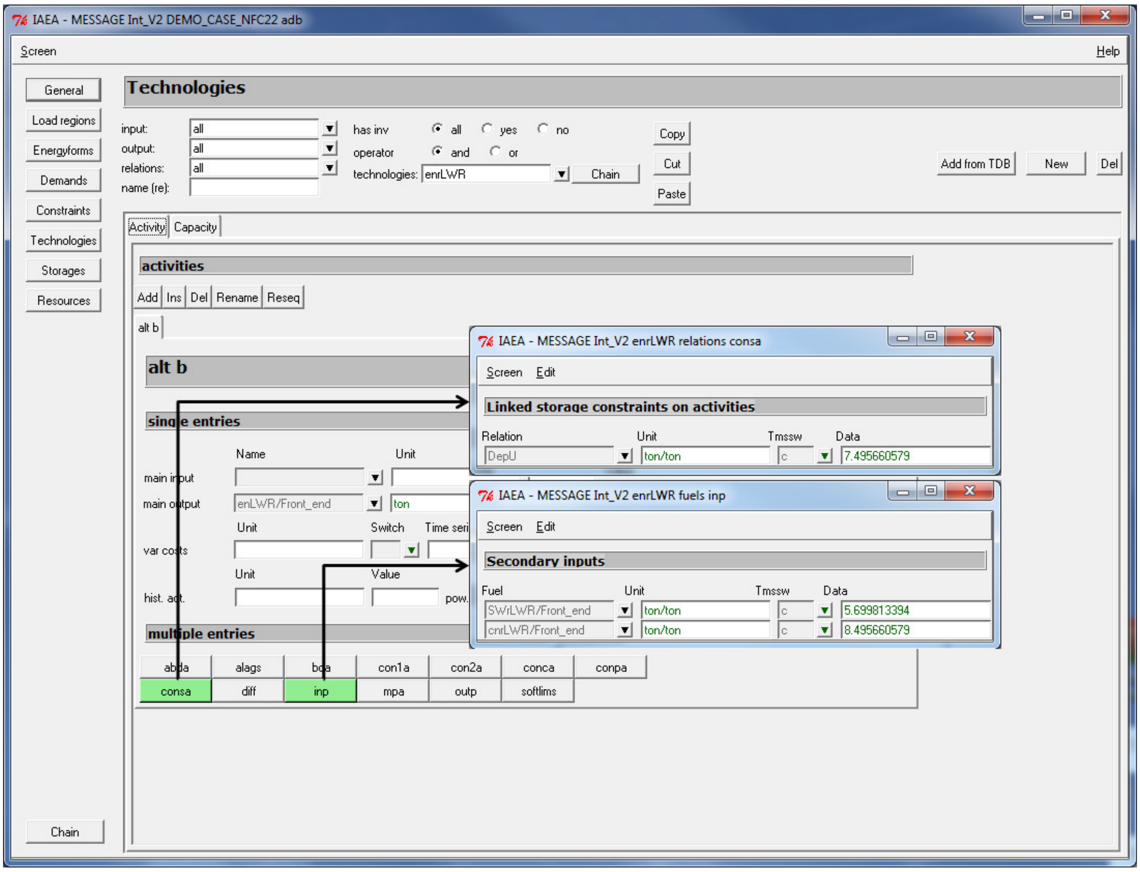
IAEA - MESSAGE Int_V2 cnLWR relations consa

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
ReUL	ton/ton	c	-1

FIG. 3.20. *Modelling LWR conversion technology.*

In the case of the modelling of re-enrichment of reprocessed uranium (see Figs 3.18 and 3.21), around 8.5 units (≈ 12.4/1.45) of converted uranium, 5.7 units (= 8.29/1.45) of SWU and 7.5 units (= 8.5 − 1) of depleted uranium will be required to obtain one unit of re-enriched uranium. For separative work related to the re-enrichment of reprocessed uranium, around 20% additional cost is added (see Fig. 3.22).



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC22 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: enrLWR

alt b

main input:
main output: enLWR/Front_end ton
var costs:
hist. act.:

IAEA - MESSAGE Int_V2 enrLWR relations consa

Linked storage constraints on activities

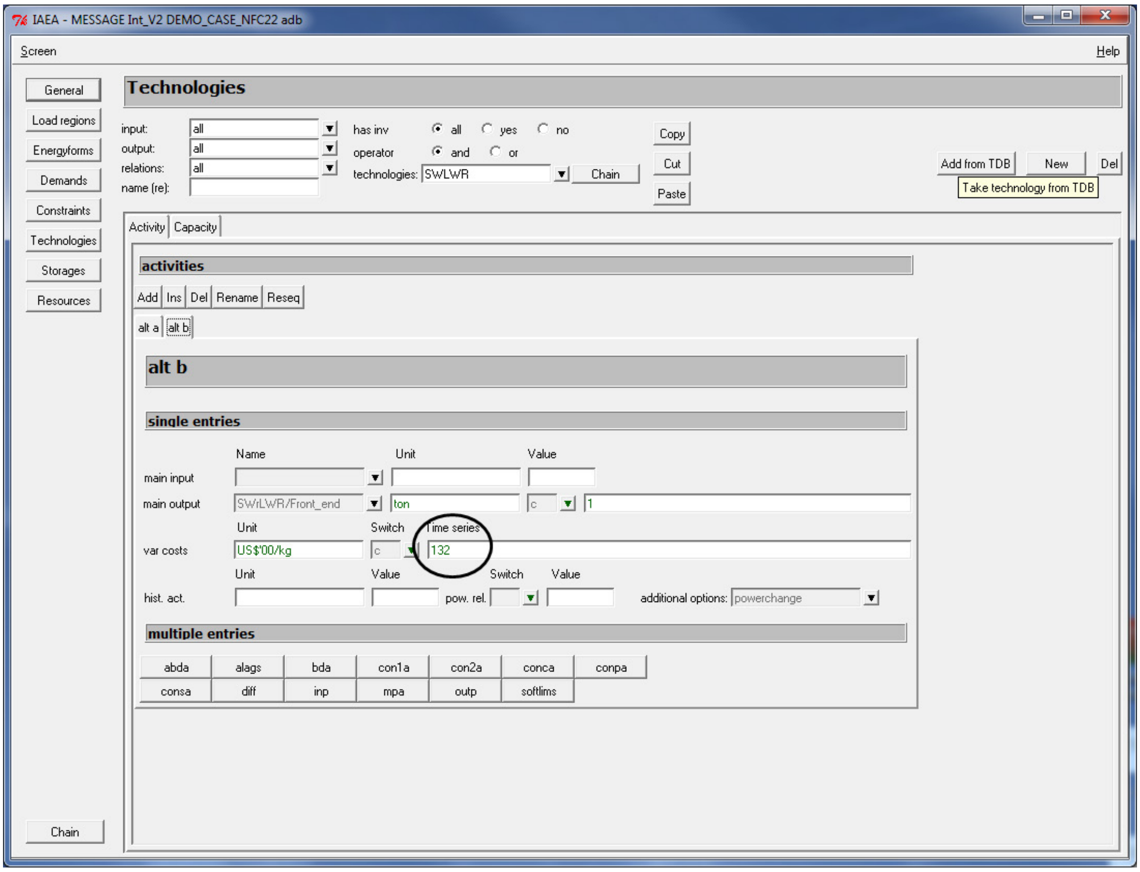
Relation	Unit	Tmssw	Data
DepU	ton/ton	c	7.495660579

IAEA - MESSAGE Int_V2 enrLWR fuels inp

Secondary inputs

Fuel	Unit	Tmssw	Data
SWrLWR/Front_end	ton/ton	c	5.699813394
cnrLWR/Front_end	ton/ton	c	8.495660579

FIG. 3.21. Modelling LWR re-enrichment technology.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC22 adb

input: all
output: all
relations: all
name (re):
technologies: SWLWR

main input: Name — ; Unit — ; Value —
main output: Name SWrLWR/Front_end; Unit ton; c; 1
var costs: Unit US$'00/kg; Switch c; Time series 132
hist. act.: Unit — ; Value — ; pow. rel.: Switch — ; Value —
additional options: powerchange

FIG. 3.22. Modelling technology SWLWR alt b.

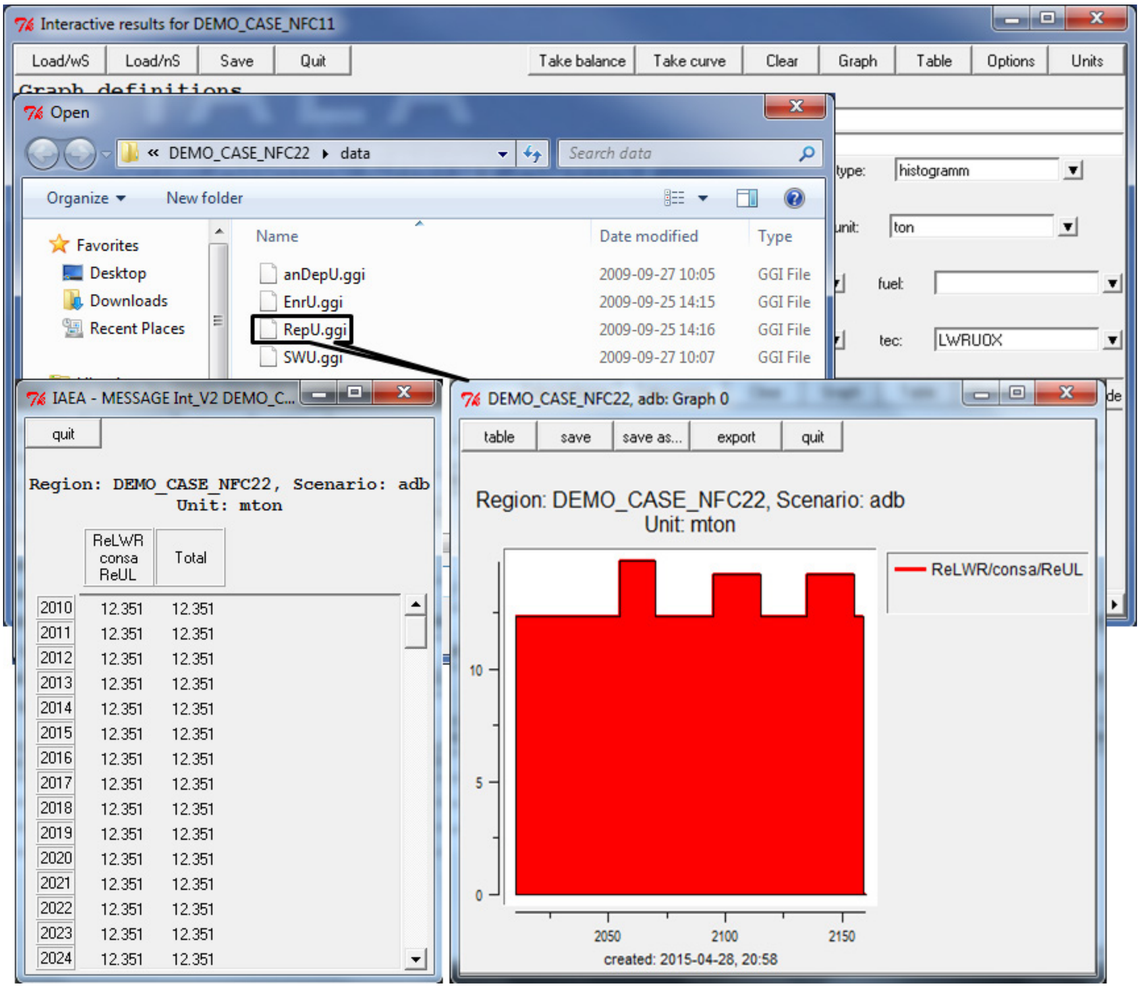
3.2.2. Mass flow MESSAGE outputs for a partially closed fuel cycle with one unit of an LWR_MOX with the recycling of reprocessed uranium

After running MESSAGE Demo_Case_NFC2, the mass flow result can be displayed in the interactive mode and compared with analytical calculations. The selected and saved results are in Table 3.9. Results can be reloaded using the tab labelled *Load/ws*.

TABLE 3.9. SELECTED MASS FLOW OUTPUTS FOR A PARTIALLY CLOSED FUEL CYCLE WITH THE RECYCLING OF REPROCESSED URANIUM

File name of results, selected and saved	Explanation
RepU.ggi	Reprocessed uranium
EnrU.ggi	Enriched uranium
anDepU.ggi	Annual depleted uranium production
SWU.ggi	Separative work unit requirement

Based on the analytical calculations, reprocessing of 13.1 t of UOX spent fuel produces 12.4 t HM of reprocessed uranium. In order to validate whether the MESSAGE results are in line, the results are compared as displayed in Figs 3.23 and 3.24. Since 12.4 t HM of reprocessed uranium is re-enriched to 1.5 t HM of UOX fresh fuel, the requirement for fresh fuel from natural uranium is decreased to the value 11.7 t HM (≈ 13.1 − 1.5). The data can be extracted from outputs of enrichment technology enLWR and additional re-enrichment technology enrLWR (see Fig. 3.24).



Name	Date modified	Type
anDepU.ggi	2009-09-27 10:05	GGI File
EnrU.ggi	2009-09-25 14:15	GGI File
RepU.ggi	2009-09-25 14:16	GGI File
SWU.ggi	2009-09-27 10:07	GGI File

type: histogramm
unit: ton
fuel:
tec: LWRUOX

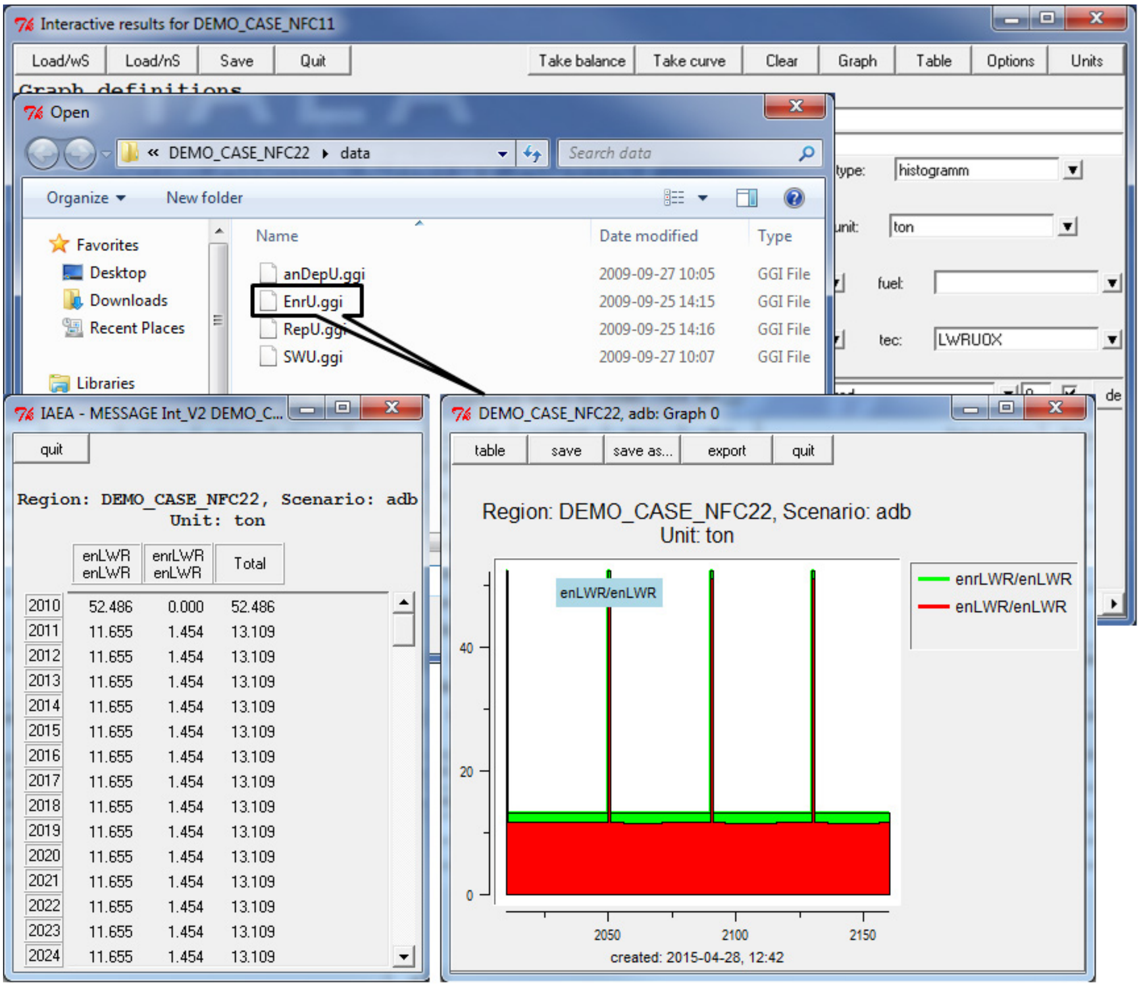
Region: DEMO_CASE_NFC22, Scenario: adb
Unit: mton

	ReLWR consa ReUL	Total
2010	12.351	12.351
2011	12.351	12.351
2012	12.351	12.351
2013	12.351	12.351
2014	12.351	12.351
2015	12.351	12.351
2016	12.351	12.351
2017	12.351	12.351
2018	12.351	12.351
2019	12.351	12.351
2020	12.351	12.351
2021	12.351	12.351
2022	12.351	12.351
2023	12.351	12.351
2024	12.351	12.351

Region: DEMO_CASE_NFC22, Scenario: adb
Unit: mton

created: 2015-04-28, 20:58

FIG. 3.23. *Reprocessed uranium.*



type: histogramm

unit: ton

fuel:

tec: LWRUOX

Name	Date modified	Type
anDepU.ggi	2009-09-27 10:05	GGI File
EnrU.ggi	2009-09-25 14:15	GGI File
RepU.ggi	2009-09-25 14:16	GGI File
SWU.ggi	2009-09-27 10:07	GGI File

Region: DEMO_CASE_NFC22, Scenario: adb
Unit: ton

	enLWR enLWR	enrLWR enLWR	Total
2010	52.486	0.000	52.486
2011	11.655	1.454	13.109
2012	11.655	1.454	13.109
2013	11.655	1.454	13.109
2014	11.655	1.454	13.109
2015	11.655	1.454	13.109
2016	11.655	1.454	13.109
2017	11.655	1.454	13.109
2018	11.655	1.454	13.109
2019	11.655	1.454	13.109
2020	11.655	1.454	13.109
2021	11.655	1.454	13.109
2022	11.655	1.454	13.109
2023	11.655	1.454	13.109
2024	11.655	1.454	13.109

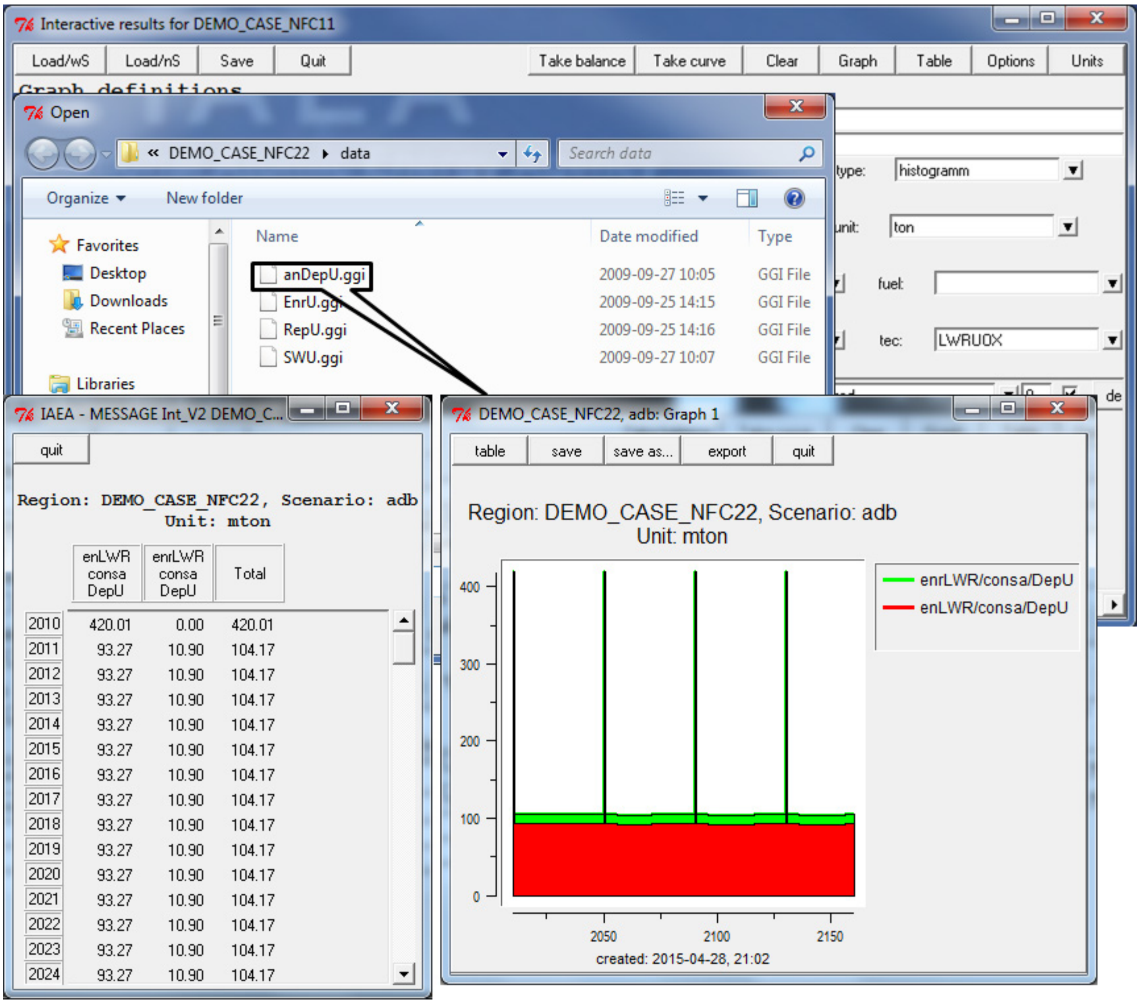
Region: DEMO_CASE_NFC22, Scenario: adb
Unit: ton

🟩 enrLWR/enLWR
🟥 enLWR/enLWR

created: 2015-04-28, 12:42

FIG. 3.24. Enriched uranium.

The consa for these technologies shows depleted uranium from enrichment of natural uranium (93.3 t HM) and from re-enrichment of reprocessed uranium (10.9 t HM) (see Fig. 3.25). The outputs of technologies SWLW and SWrLWR give the SWU requirements for enrichment of natural uranium (61.5 t SWU) and re-enrichment of reprocessed uranium (8.29 t SWU) (see Fig. 3.26).



Name	Date modified	Type
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EnrU.ggi	2009-09-25 14:15	GGI File
RepU.ggi	2009-09-25 14:16	GGI File
SWU.ggi	2009-09-27 10:07	GGI File

type: histogramm

unit: ton

fuel:

tec: LWRUOX

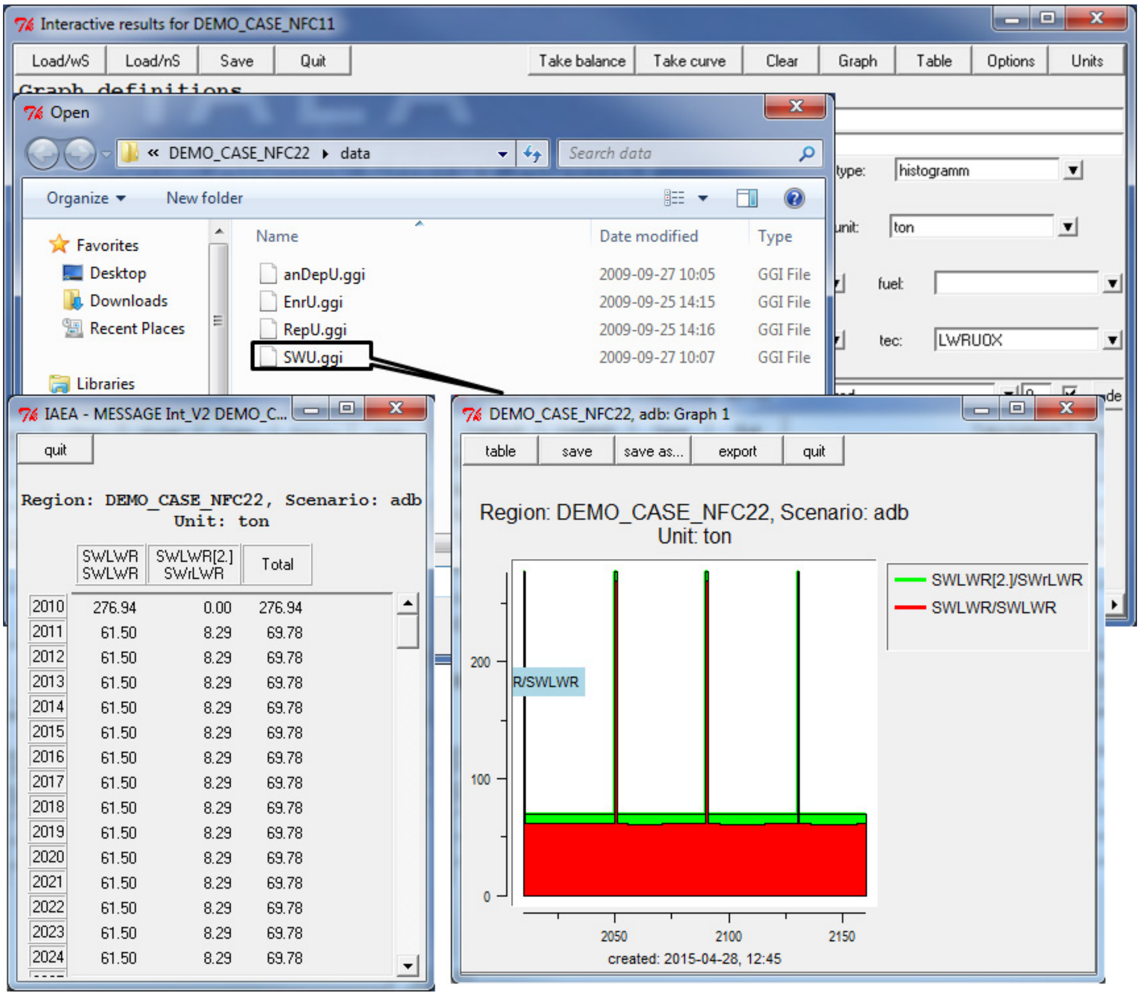
Region: DEMO_CASE_NFC22, Scenario: adb
Unit: mton

	enLWR consa DepU	enrLWR consa DepU	Total
2010	420.01	0.00	420.01
2011	93.27	10.90	104.17
2012	93.27	10.90	104.17
2013	93.27	10.90	104.17
2014	93.27	10.90	104.17
2015	93.27	10.90	104.17
2016	93.27	10.90	104.17
2017	93.27	10.90	104.17
2018	93.27	10.90	104.17
2019	93.27	10.90	104.17
2020	93.27	10.90	104.17
2021	93.27	10.90	104.17
2022	93.27	10.90	104.17
2023	93.27	10.90	104.17
2024	93.27	10.90	104.17

Region: DEMO_CASE_NFC22, Scenario: adb
Unit: mton

created: 2015-04-28, 21:02

FIG. 3.25. Annual depleted uranium production.



type: histogramm

unit: ton

fuel:

tec: LWRUOX

Name	Date modified	Type
anDepU.ggi	2009-09-27 10:05	GGI File
EnrU.ggi	2009-09-25 14:15	GGI File
RepU.ggi	2009-09-25 14:16	GGI File
SWU.ggi	2009-09-27 10:07	GGI File

Region: DEMO_CASE_NFC22, Scenario: adb
Unit: ton

	SWLWR SWLWR	SWLWR[2.] SWrLWR	Total
2010	276.94	0.00	276.94
2011	61.50	8.29	69.78
2012	61.50	8.29	69.78
2013	61.50	8.29	69.78
2014	61.50	8.29	69.78
2015	61.50	8.29	69.78
2016	61.50	8.29	69.78
2017	61.50	8.29	69.78
2018	61.50	8.29	69.78
2019	61.50	8.29	69.78
2020	61.50	8.29	69.78
2021	61.50	8.29	69.78
2022	61.50	8.29	69.78
2023	61.50	8.29	69.78
2024	61.50	8.29	69.78

Region: DEMO_CASE_NFC22, Scenario: adb
Unit: ton

created: 2015-04-28, 12:45

FIG. 3.26. SWU requirement.

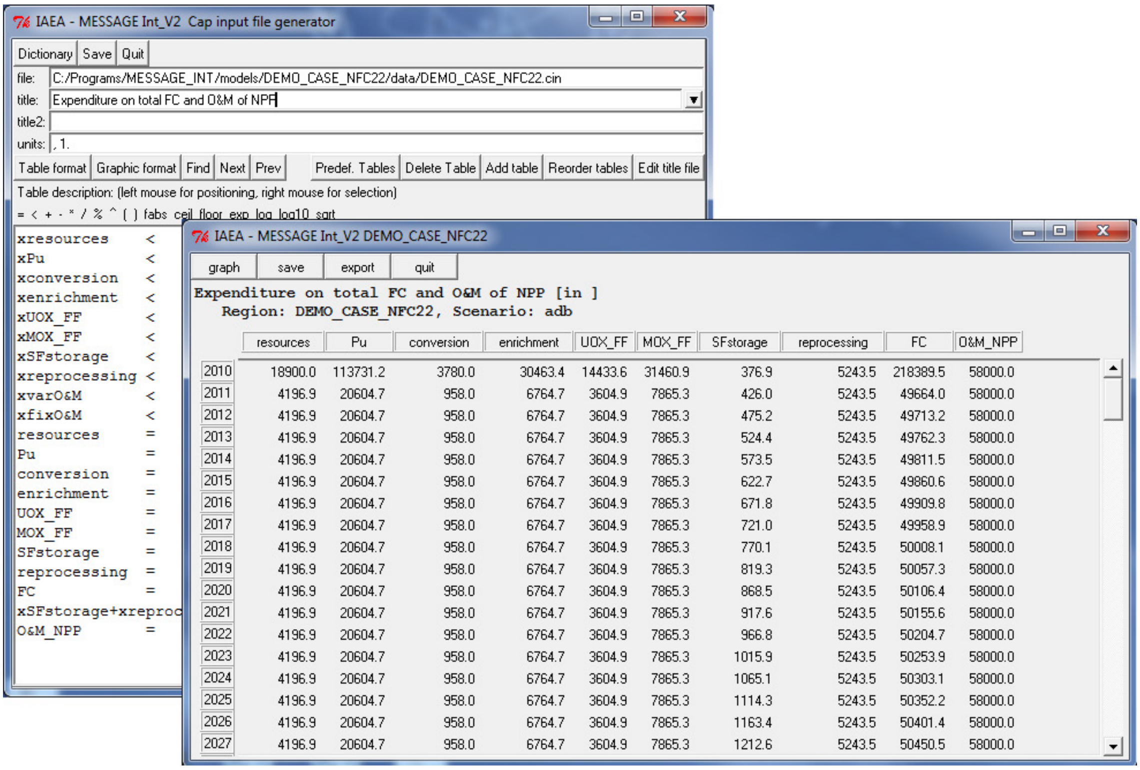
3.2.3. Economic results of MESSAGE modelling for a partially closed fuel cycle with one unit of an LWR_MOX with the recycling of reprocessed uranium

The economic results are extracted through a cin file, prepared in the same way as in Demo_Case_NFC1. Three tables were prepared to calculate the following results:

— Annual investments in the NPP;
— Annual expenditure on the total fuel cycle and O&M of the NPP;
— LUAC&LUOM.

As in the case in Section 3.2.2, annual investments in the NPP were prepared with the tab labelled *Predef. Tables*. Investments and other costs are measured by multiplying US $1000 to the capacity, since capacity has the unit MW and overnight cost has the unit US $/kW (MW × US $/kW = US $1000). The result for annual investment in LWR_MOX is US $3 billion in 2009 (= 3×10^6 × US $1000). Fuel cycle expenditure includes resources, conversion, enrichment, UOX and MOX fresh fuel fabrication, reprocessing and spent fuel storage. Expenditure on each fuel cycle step is obtained by multiplying the amount of material for a given step by the corresponding specific cost.

The economic results are the same as the results without the recycling of reprocessed uranium for annual investment costs, annual expenditure on total O&M of the NPP and levelized cost. Differences result only in the annual expenditure on the total fuel cycle (see Fig. 3.27).



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC22/data/DEMO_CASE_NFC22.cin
title: Expenditure on total FC and O&M of NPP
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)

= < + - * / % ^ ( ) fabs ceil floor exp log log10 sqrt

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xresources     <
xPu            <
xconversion    <
xenrichment    <
xUOX_FF        <
xMOX_FF        <
xSFstorage     <
xreprocessing  <
xvarO&M        <
xfixO&M        <
resources      =
Pu             =
conversion     =
enrichment     =
UOX_FF         =
MOX_FF         =
SFstorage      =
reprocessing   =
FC             =
xSFstorage+xreproc
O&M_NPP        =
```

Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC22, Scenario: adb

	resources	Pu	conversion	enrichment	UOX_FF	MOX_FF	SFstorage	reprocessing	FC	O&M_NPP
2010	18900.0	113731.2	3780.0	30463.4	14433.6	31460.9	376.9	5243.5	218389.5	58000.0
2011	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	426.0	5243.5	49664.0	58000.0
2012	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	475.2	5243.5	49713.2	58000.0
2013	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	524.4	5243.5	49762.3	58000.0
2014	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	573.5	5243.5	49811.5	58000.0
2015	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	622.7	5243.5	49860.6	58000.0
2016	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	671.8	5243.5	49909.8	58000.0
2017	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	721.0	5243.5	49958.9	58000.0
2018	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	770.1	5243.5	50008.1	58000.0
2019	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	819.3	5243.5	50057.3	58000.0
2020	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	868.5	5243.5	50106.4	58000.0
2021	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	917.6	5243.5	50155.6	58000.0
2022	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	966.8	5243.5	50204.7	58000.0
2023	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	1015.9	5243.5	50253.9	58000.0
2024	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	1065.1	5243.5	50303.1	58000.0
2025	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	1114.3	5243.5	50352.2	58000.0
2026	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	1163.4	5243.5	50401.4	58000.0
2027	4196.9	20604.7	958.0	6764.7	3604.9	7865.3	1212.6	5243.5	50450.5	58000.0

FIG. 3.27. Annual expenditure on the fuel cycle and O&M of the NPP.

3.3. A GLOBAL NES BASED ON AN LWR, AN HWR AND AN LWR_MOX WITH A PARTIALLY CLOSED FUEL CYCLE (DEMO_CASE_NFC23)

To apply MESSAGE to analyse the NES based on thermal reactors with once plutonium recycling nuclear fuel cycle at a global level, the following reactors and fuels are considered:

- An HWR using natural uranium fuel;
- An LWR using UOX fuel;
- An LWR using UOX and MOX fuels.

The average annual new capacity growth is no greater than 1% for reactor LWR_MOX. Other calculation conditions and assumptions are comparable to the global MESSAGE model for NFC1. The scheme of the nuclear fuel cycle is presented in Fig. 3.28.

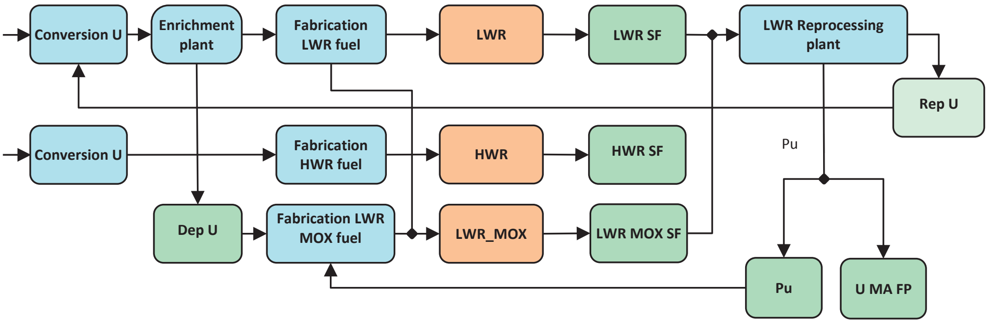
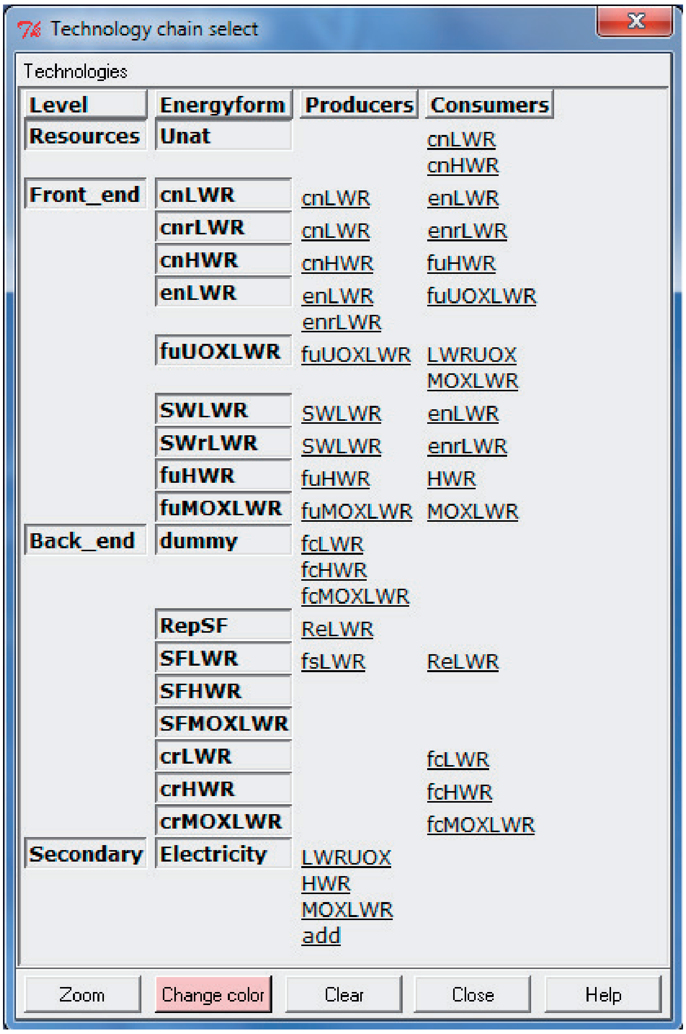


FIG. 3.28. *Scheme of a global NES based on thermal reactors with partially closed fuel cycle.*

Calculations of reprocessed products are based on the composition of UOX spent fuel after five years cooling and one year of reprocessing. The decay of unstable isotopes in interim storage before reprocessing and the decay of plutonium and minor actinides in stock are not taken into account. The energy chain of this NES is shown in Fig. 3.29. Input data for LWR and HWR technologies can be taken from Demo_Case_NFC1.



Level	Energyform	Producers	Consumers
Resources	Unat		cnLWR cnHWR
Front_end	cnLWR	cnLWR	enLWR
	cnrLWR	cnLWR	enrLWR
	cnHWR	cnHWR	fuHWR
	enLWR	enLWR enrLWR	fuUOXLWR
	fuUOXLWR	fuUOXLWR	LWRUOX MOXLWR
	SWLWR	SWLWR	enLWR
	SWrLWR	SWLWR	enrLWR
	fuHWR	fuHWR	HWR
	fuMOXLWR	fuMOXLWR	MOXLWR
Back_end	dummy	fcLWR fcHWR fcMOXLWR	
	RepSF	ReLWR	
	SFLWR	fsLWR	ReLWR
	SFHWR		
	SFMOXLWR		
	crLWR		fcLWR
	crHWR		fcHWR
	crMOXLWR		fcMOXLWR
Secondary	Electricity	LWRUOX HWR MOXLWR add	

FIG. 3.29. *Energy chain of the NES.*

3.3.1. Mass flow MESSAGE outputs for a partially closed fuel cycle

The following results are extracted and analysed:

- — Nuclear electricity generation structure;
- — Fresh fuel requirements;
- — Natural uranium consumption;
- — Reprocessing requirements.

Figure 3.30 displays the structure of nuclear electricity generation. In this scenario, demand for the HWR is set at 6% of the total demand for thermal reactors, while annual growth on new LWR_MOX capacities is restricted to no more than 1% per year. The LWR_MOX systems are commissioned from 2030. The consumption of natural uranium over a 100 year period is about 42 million tonnes (see Fig. 3.31). Ultimate uranium resources (identified, prognosticated and speculative) are estimated at 16 million tonnes and are exhausted by 2070. Uranium is recovered from phosphates from 2070, until it is exhausted by 2097, when natural uranium from sea water is used.

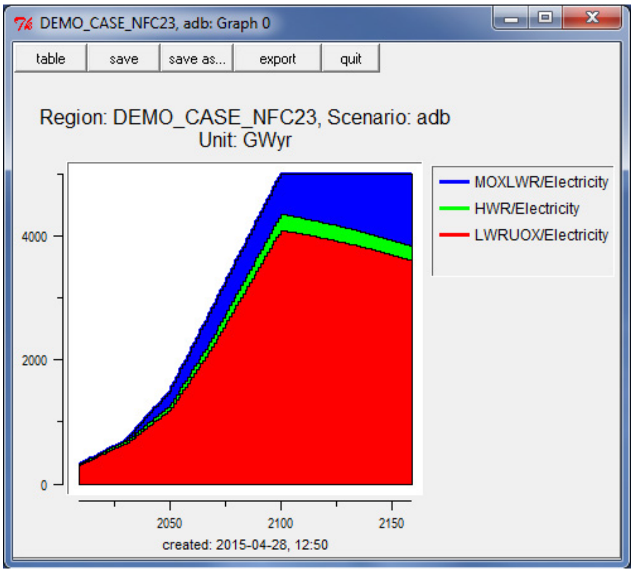


FIG. 3.30. Nuclear electricity generation structure.

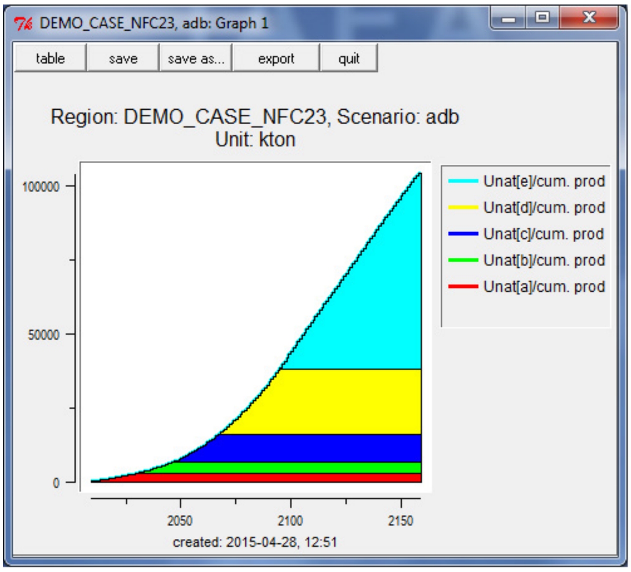


FIG. 3.31. Cumulative natural uranium consumption.

Fuel cycle facilities requirements such as enrichment, UOX/MOX fuel fabrication and spent nuclear fuel reprocessing can be extracted from the model. UOX fuel fabrication will reach about 120 kt/a for the LWR and 44 kt/a for the HWR by the end of the century. The MOX fuel fabrication requirement is about 6 kt/a (see Fig. 3.32). Spent fuel reprocessing achieves 42 kt/a by the end of time period (see Fig. 3.33), operating at full capacity.

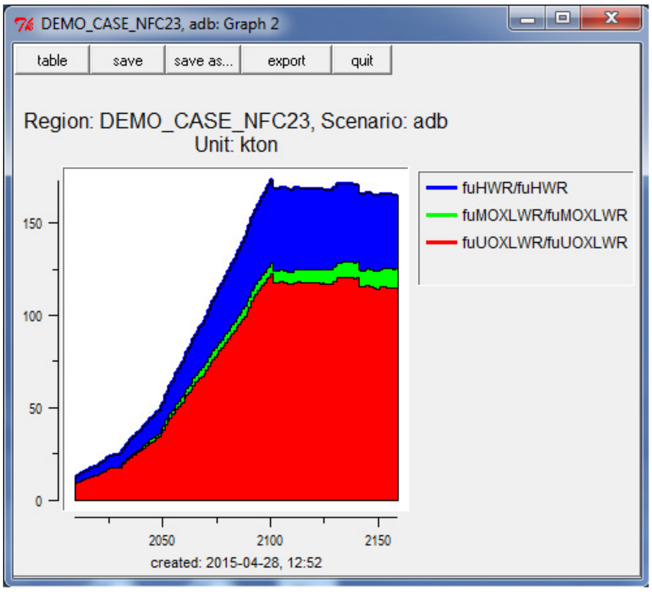


FIG. 3.32. Fresh fuel requirement.

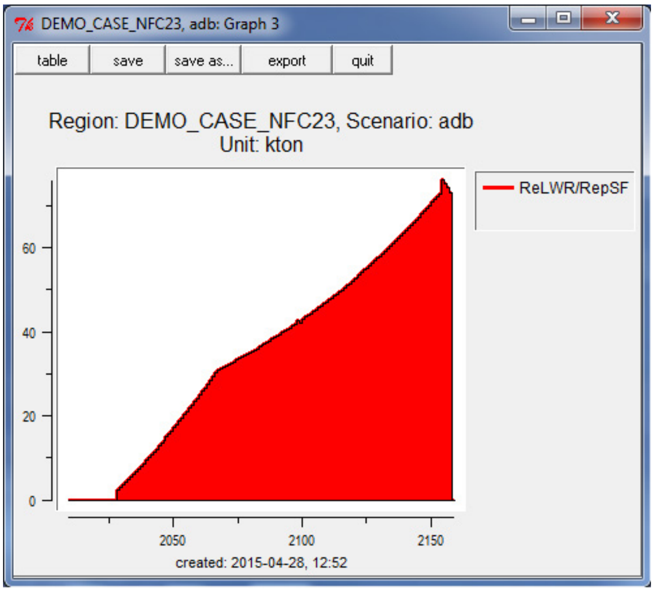


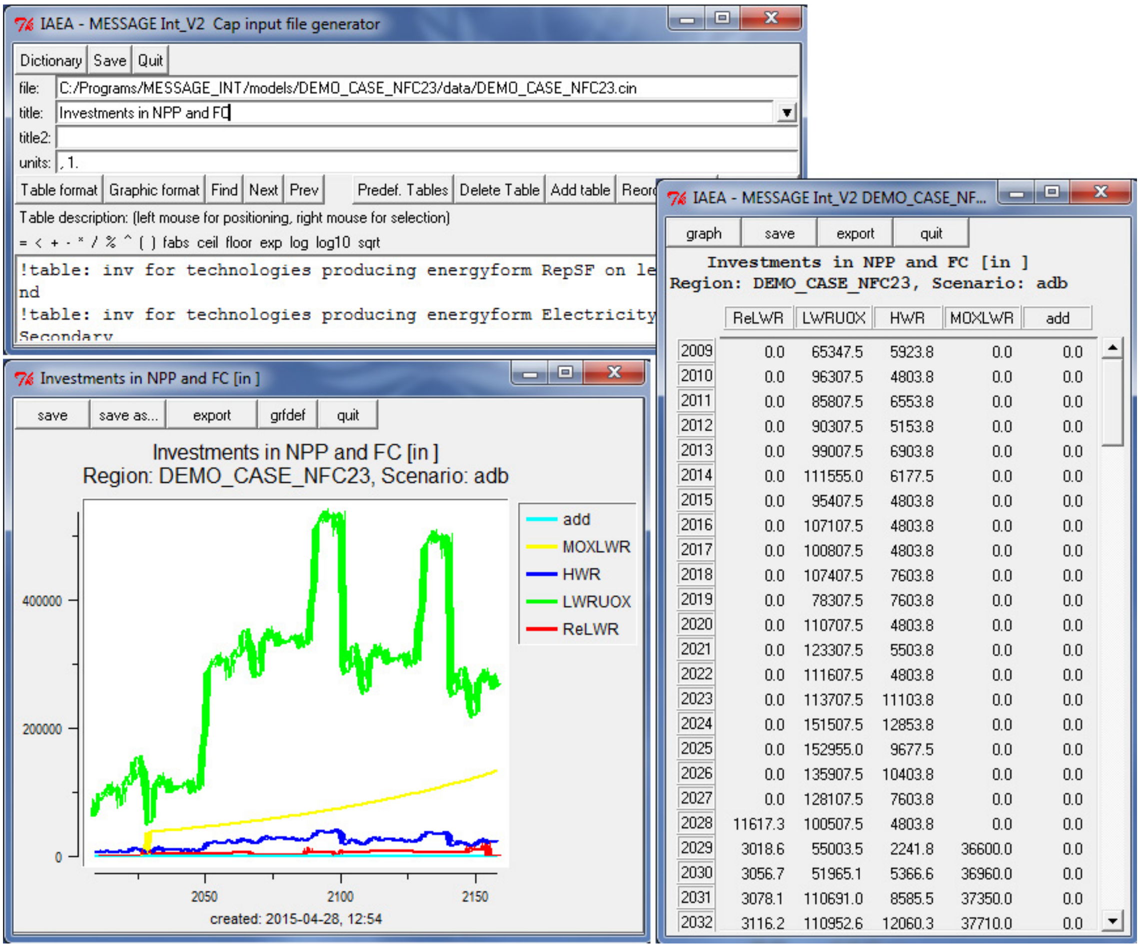
FIG. 3.33. Reprocessing spent fuel requirement.

3.3.2. Economic results of MESSAGE modelling for a partially closed fuel cycle

The economic results can be extracted through a cin file. Three tables were prepared to calculate the following results:

- — Annual investments in the NPP;
- — Annual expenditure on the fuel cycle and O&M of the NPP;
- — LUAC&LUOM.

Annual investments in the NPP are given in Fig. 3.34, prepared with the help of the tab labelled *Predef. Tables*. Investments and other costs are measured in millions of US dollars, since capacity has the unit GW and overnight cost has the unit US $/kW (GW × US $/kW = US $1 million). The results for annual investment in LWR_UOX and LWR_MOX are given in the graph and table in Fig. 3.34.



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title: Investments in NPP and FC
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)

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!table: inv for technologies producing energyform RepSF on le
nd
!table: inv for technologies producing energyform Electricity
Secondary
```

Investments in NPP and FC [in]
Region: DEMO_CASE_NFC23, Scenario: adb

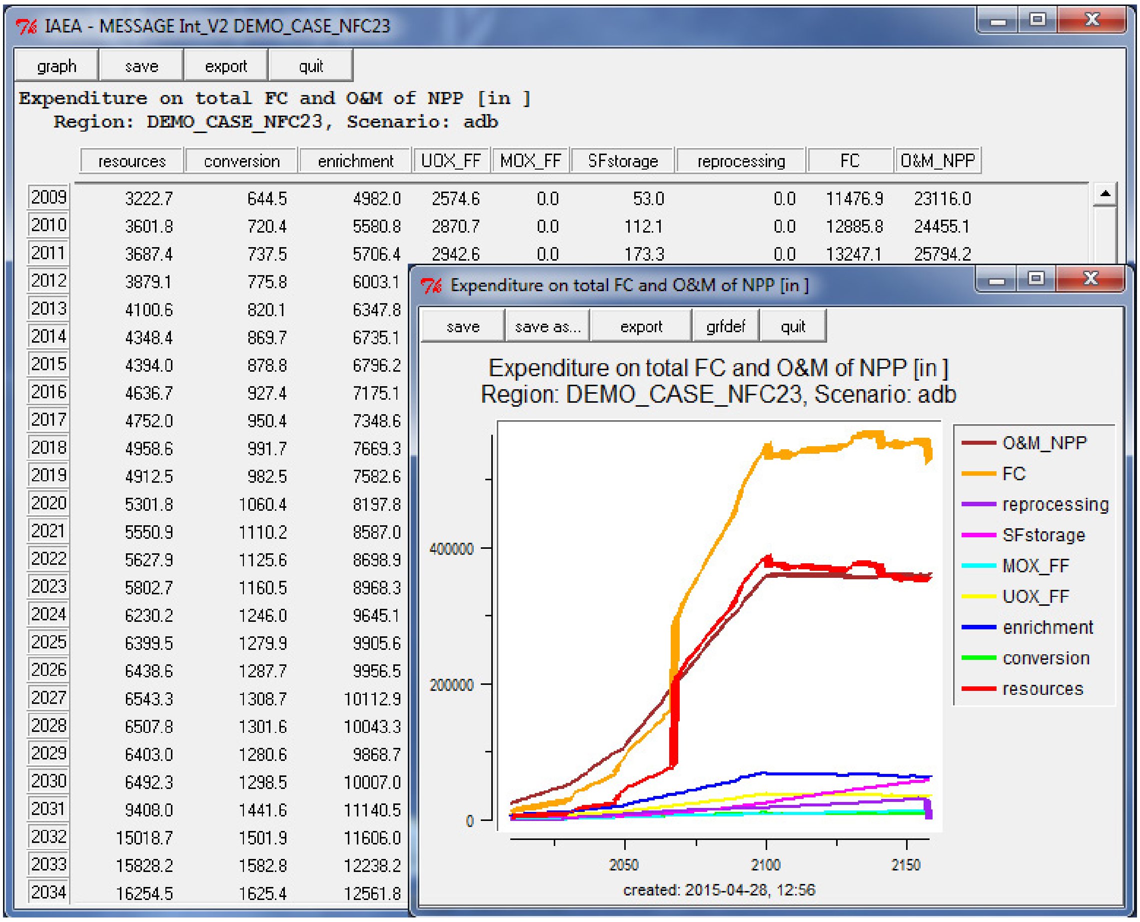
created: 2015-04-28, 12:54

Investments in NPP and FC [in]
Region: DEMO_CASE_NFC23, Scenario: adb

	ReLWR	LWRUOX	HWR	MOXLWR	add
2009	0.0	65347.5	5923.8	0.0	0.0
2010	0.0	96307.5	4803.8	0.0	0.0
2011	0.0	85807.5	6553.8	0.0	0.0
2012	0.0	90307.5	5153.8	0.0	0.0
2013	0.0	99007.5	6903.8	0.0	0.0
2014	0.0	111555.0	6177.5	0.0	0.0
2015	0.0	95407.5	4803.8	0.0	0.0
2016	0.0	107107.5	4803.8	0.0	0.0
2017	0.0	100807.5	4803.8	0.0	0.0
2018	0.0	107407.5	7603.8	0.0	0.0
2019	0.0	78307.5	7603.8	0.0	0.0
2020	0.0	110707.5	4803.8	0.0	0.0
2021	0.0	123307.5	5503.8	0.0	0.0
2022	0.0	111607.5	4803.8	0.0	0.0
2023	0.0	113707.5	11103.8	0.0	0.0
2024	0.0	151507.5	12853.8	0.0	0.0
2025	0.0	152955.0	9677.5	0.0	0.0
2026	0.0	135907.5	10403.8	0.0	0.0
2027	0.0	128107.5	7603.8	0.0	0.0
2028	11617.3	100507.5	4803.8	0.0	0.0
2029	3018.6	55003.5	2241.8	36600.0	0.0
2030	3056.7	51965.1	5366.6	36960.0	0.0
2031	3078.1	110691.0	8585.5	37350.0	0.0
2032	3116.2	110952.6	12060.3	37710.0	0.0

FIG. 3.34. Annual investments in the NPP.

Annual expenditure on the fuel cycle and O&M of the NPP is given in Fig. 3.35. Expenditure on the fuel cycle includes resources, conversion, enrichment, UOX and MOX fresh fuel fabrication, reprocessing and spent fuel storage costs. Annual expenditure on O&M of the NPP (fixed and variable O&M) was also calculated. Costs and investment are measured in millions of US dollars.

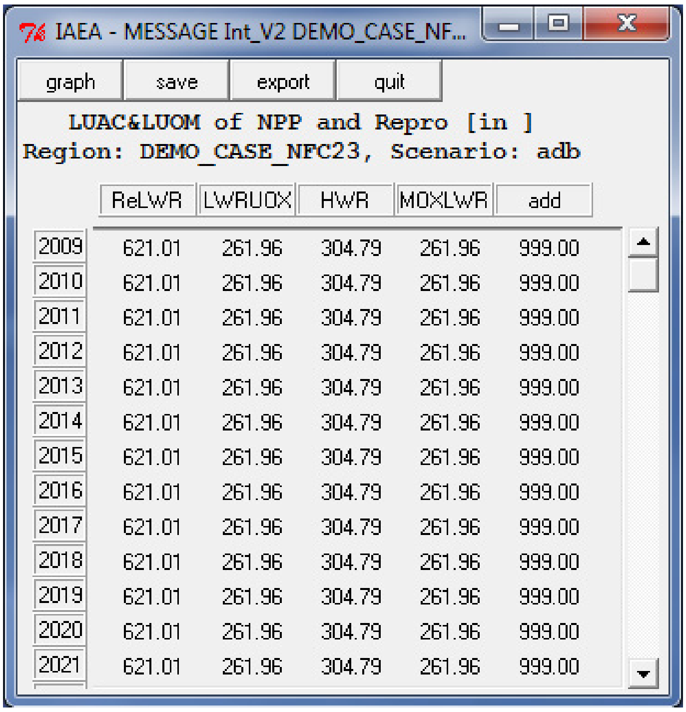


Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC23, Scenario: adb

	resources	conversion	enrichment	UOX_FF	MOX_FF	SFstorage	reprocessing	FC	O&M_NPP
2009	3222.7	644.5	4982.0	2574.6	0.0	53.0	0.0	11476.9	23116.0
2010	3601.8	720.4	5580.8	2870.7	0.0	112.1	0.0	12885.8	24455.1
2011	3687.4	737.5	5706.4	2942.6	0.0	173.3	0.0	13247.1	25794.2
2012	3879.1	775.8	6003.1						
2013	4100.6	820.1	6347.8						
2014	4348.4	869.7	6735.1						
2015	4394.0	878.8	6796.2						
2016	4636.7	927.4	7175.1						
2017	4752.0	950.4	7348.6						
2018	4958.6	991.7	7669.3						
2019	4912.5	982.5	7582.6						
2020	5301.8	1060.4	8197.8						
2021	5550.9	1110.2	8587.0						
2022	5627.9	1125.6	8698.9						
2023	5802.7	1160.5	8968.3						
2024	6230.2	1246.0	9645.1						
2025	6399.5	1279.9	9905.6						
2026	6438.6	1287.7	9956.5						
2027	6543.3	1308.7	10112.9						
2028	6507.8	1301.6	10043.3						
2029	6403.0	1280.6	9868.7						
2030	6492.3	1298.5	10007.0						
2031	9408.0	1441.6	11140.5						
2032	15018.7	1501.9	11606.0						
2033	15828.2	1582.8	12238.2						
2034	16254.5	1625.4	12561.8						

FIG. 3.35. Annual expenditure on the fuel cycle and O&M of the NPP.

LUAC&LUOM for the NPP was prepared with the tab labelled *Predef. Tables*. The results in US \$/kW·a are 261.96, 261.96 and 304.79 for an LWR_UOX, an LWR_MOX and an HWR, respectively (see Fig. 3.36). LUAC&LUOM for the reprocessing plant is US \$621/kg SF.



LUAC&LUOM of NPP and Repro [in]
Region: DEMO_CASE_NFC23, Scenario: adb

	ReLWR	LWRUOX	HWR	MOXLWR	add
2009	621.01	261.96	304.79	261.96	999.00
2010	621.01	261.96	304.79	261.96	999.00
2011	621.01	261.96	304.79	261.96	999.00
2012	621.01	261.96	304.79	261.96	999.00
2013	621.01	261.96	304.79	261.96	999.00
2014	621.01	261.96	304.79	261.96	999.00
2015	621.01	261.96	304.79	261.96	999.00
2016	621.01	261.96	304.79	261.96	999.00
2017	621.01	261.96	304.79	261.96	999.00
2018	621.01	261.96	304.79	261.96	999.00
2019	621.01	261.96	304.79	261.96	999.00
2020	621.01	261.96	304.79	261.96	999.00
2021	621.01	261.96	304.79	261.96	999.00

FIG. 3.36. LUAC&LUOM for the NPP.

4. DEMONSTRATION CASE 3: AN NES BASED ON THERMAL AND FAST REACTORS WITH A CLOSED FUEL CYCLE

The modelling of a closed fuel cycle is divided into the following parts:

- A closed fuel cycle with one unit of FR_MOX with plutonium multi-recycling;
- A global NES based on thermal and fast reactors with the recycling of plutonium recovered from an LWR and multiple recycling of plutonium recovered from a fast reactor.

4.1. A CLOSED FUEL CYCLE WITH ONE UNIT OF FR_MOX WITH PLUTONIUM MULTI-RECYCLING

For simplicity, the model simulates one unit of a fast reactor, FR_MOX. The FR_MOX unit has 870 MW(e) of installed capacity, with the capacity factor of 85%. In addition, it is assumed that the demand has been set to equal supply of the nuclear power unit, namely 740 MW·a. Demand has been set constant for the time period 2009–2160. The fast reactor uses MOX fuel for the core and depleted uranium for the blankets (see Fig. 4.1). The fast reactor breeding ratio is approximately one. All nuclear fuel cycle processes have some material losses. However, only reprocessing losses are taken into account in this case. All other process losses are assumed to be zero.

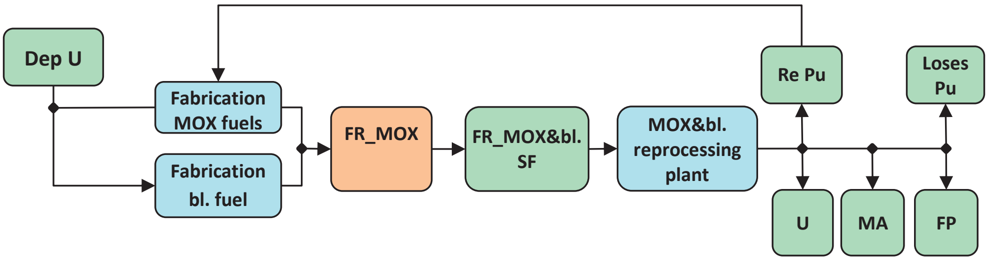


FIG. 4.1. An FR_MOX fuel cycle diagram.

As in the other cases, the technical and economic data of FR_MOX and its fuel cycle are based on actual reference data as given in Tables 4.1–4.3. The nuclide group composition (mix of MOX + blankets) is based on two years of expected cooling, and reprocessed products are based on one year of reprocessing. Decay of plutonium and minor actinides in stock is not taken into account in this calculation.

TABLE 4.1. REACTOR CHARACTERISTICS

Item	Symbol	Unit	FR_MOX		
Nuclear capacity	NC	MW(e)	870		
Thermal efficiency (electricity)	Eff	n.a.[a]	0.414 3		
Load factor	Lf	n.a.[a]	0.85		
Cooling time	a	a	2		
Plant lifetime	a	a	60		
Construction time	a	a	5		
			Core	Axial blanket	Radial blanket
Fuel residence time	Tr	EFPD	420	420	490
Discharged burnup	Bu	MW·d/t HM	65.9	4.8	4.2
First loading	FuLoad	t HM	12.6	5.5	6.2
Plutonium content	TotPuFF	n.a.[a]	0.218	DepU	DepU

[a] n.a.: not applicable.

TABLE 4.2. NUCLIDE GROUP COMPOSITION OF MIX MOX AND BLANKET SPENT FUEL AFTER TWO YEARS COOLING AND ONE YEAR REPROCESSING

Item	Symbol	Factor
Uranium total	TotUSF	0.840 4
Plutonium total	TotPuSF	0.118 9
Minor actinides	TotMASF	0.002 3
Fission products	TotFPSF	0.038 4
Heavy metal	TotHMSF	0.961 6

TABLE 4.3. ECONOMIC PARAMETERS OF FR_MOX AND ITS FUEL CYCLE

Item	Unit	Reference value
Investment cost	US $/kW(e)	3500
Fixed O&M cost	US $/kW/a	55
Variable O&M cost	US $/kW·a	50
MOX fuel fabrication	US $/kg HM	1500
Blanket fuel fabrication	US $/kg HM	300
Cooling storage	US $/kg HM/a	7.5
Interim storage	US $/kg HM/a	7
Reprocessing	US $/kg HM	1500
Separated plutonium storage	US $/kg HM/a	2000

Front end fuel cycle (fuel fabrication) is modelled as a fuel cycle service in this model. Reprocessing is modelled as a facility. Technical and economic parameters of reprocessing facility are given in Table 4.4.

TABLE 4.4. REPROCESSING FACILITY CHARACTERISTICS

Item	Unit	LWR fuel	FR fuel
Capacity	t HM/a	1000	1000
Capacity factor of use	%	100	100
Construction time	a	5	5
Operational life	a	60	60
Reprocessing time	a	1	1
Investment cost	US $/kg HM	5000	5000
Annual operational cost	US $/kg HM/a	400	1000
Total service cost (at 4% discount rate)	US $/kg HM	650	1250
Reprocessing losses	%	≤1 (0.755)	≤1 (0.755)

4.1.1. Mathematical mass flow calculation for a closed fuel cycle with one unit of FR_MOX and plutonium multi-recycling

The average annual nuclear material flow for each step of a closed fuel cycle option (see Fig. 4.1) can be estimated based on the technical data of reactor and its fuel cycle (see Tables 4.1–4.4). The following are some analytical equations for mass flow calculations:

(a) Annual fresh fuel loading:

$$\mathrm{FF}_i = \frac{365 \times \mathrm{Lf} \times \mathrm{FuLoad}_i}{\mathrm{Tr}_i} \tag{4.1}$$

where i = {Core, Rad, Ax}

(b) Spent fuel discharged:

$$\mathrm{SFD} = \mathrm{FFMOX} + \mathrm{FFAx} + \mathrm{FFRad} \tag{4.2}$$

(c) Reprocessed plutonium used:

$$\mathrm{RepPuUsed} = \mathrm{FFMOX} \times \mathrm{TotPuFF} \tag{4.3}$$

(d) Spent fuel reprocessing:

$$\mathrm{SFR} = \min\left\{\mathrm{SFD},\ \frac{\mathrm{RepPuUsed}}{\mathrm{TotPuSF} \times (1 - \mathrm{RepLos})}\right\} \tag{4.4}$$

where RepLos is the reprocessing losses factor

(e) Reprocessed plutonium:

$$\mathrm{RepPu} = \mathrm{SFR} \times \mathrm{TotPuSF} \times (1 - \mathrm{RepLos}) \tag{4.5}$$

(f) Plutonium losses:

$$\mathrm{LosPu} = \mathrm{SFR} \times \mathrm{TotPuSF} \times \mathrm{RepLos} \tag{4.6}$$

(g) Minor actinides:

$$\mathrm{RepMA} = \mathrm{SFR} \times \mathrm{TotMASF} \tag{4.7}$$

(h) Fission products:

$$\mathrm{RepFP} = \mathrm{SFR} \times \mathrm{TotFPSF} \tag{4.8}$$

The results of the analytical calculations for mass flow of FR_MOX fuel cycle are based on Eqs (4.1)–(4.8) as presented in Table 4.5 and Fig. 4.2.

TABLE 4.5. ANALYTICAL MASS FLOW CALCULATIONS

Annual output parameters	Symbol	Unit	Equation	Analytical result
Fresh fuel MOX	FFMOX	t HM	(4.1, *i* = Core)	9.336
Fresh fuel axial blanket	FFAx	t HM	(4.1, *i* = Ax)	4.063
Fresh fuel radial blanket	FFRad	t HM	(4.1, *i* = Rad)	3.894
Spent fuel discharged	SFD	t HM + t FP	(4.2)	17.294
Reprocessed plutonium used	RepPuUsed	t HM	(4.3)	2.040
Spent fuel reprocessing	SFR	t HM + t FP	(4.4)	17.294
Reprocessed plutonium	RepPu	t HM	(4.5)	2.040
Plutonium losses	LosPu	t HM	(4.6)	0.016
Minor actinides	RepMA	t HM	(4.7)	0.040
Fission products	RepFP	t	(4.8)	0.664

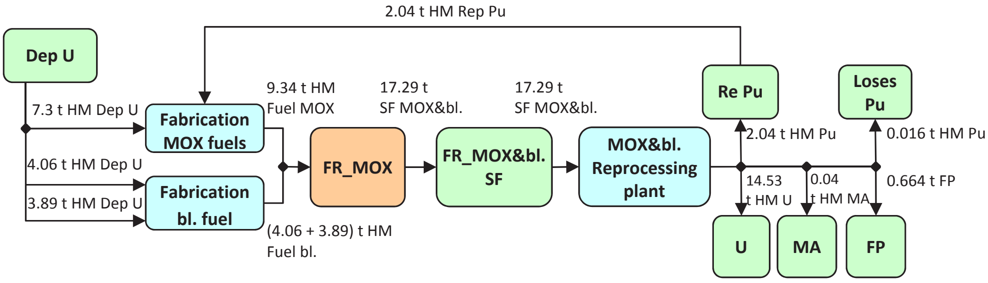
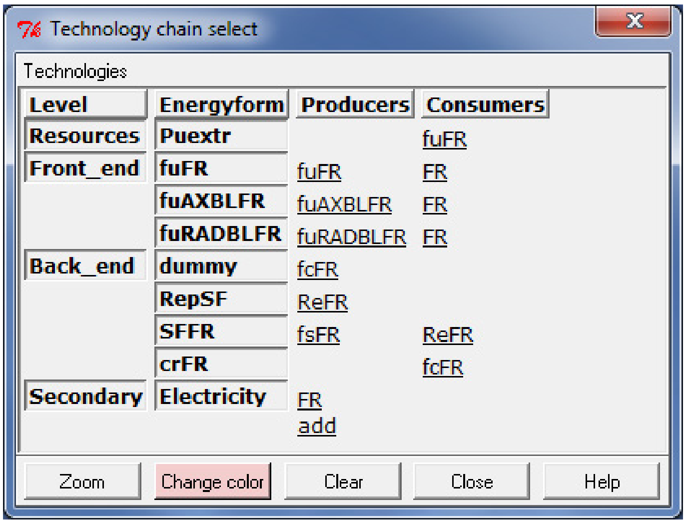


FIG. 4.2. Mass balance of the FR_MOX fuel cycle.

The FR_MOX reactor consumes 9.336 t HM of MOX fuel for the core and 4.063 t HM and 3.894 t HM for the blankets (axial and radial, respectively). MOX fuel is fabricated from 7.3 t HM of depleted uranium and 2.04 t HM of reprocessed plutonium. After irradiation in the reactor, the total value of spent fuel (17.294 t), including fission products, is discharged from the reactor. The fuel discharged from the core and blankets are reprocessed together. The reprocessing of 17.294 t HM total mixed spent fuel provides 2.056 t HM of plutonium, slightly more than is actual required to produce 9.336 t HM of MOX fuel. The over-production (production − consumption) of plutonium (0.016 t HM) is assumed to be treated as losses, which is assumed a spent nuclear fuel reprocessing loss rate of 0.75% for plutonium. This means fast reactors have a self-sustaining fuel cycle with respect to the plutonium supply. However, the self-sustaining fuel cycle can only be achieved when plutonium becomes available three years after start up (cooling + reprocessing time). Plutonium for the first loading and three years of operation should be delivered from an external source.

Figure 4.3 shows the energy and technology chain of a closed fuel cycle option with one unit of FR_MOX and plutonium multi-recycling.

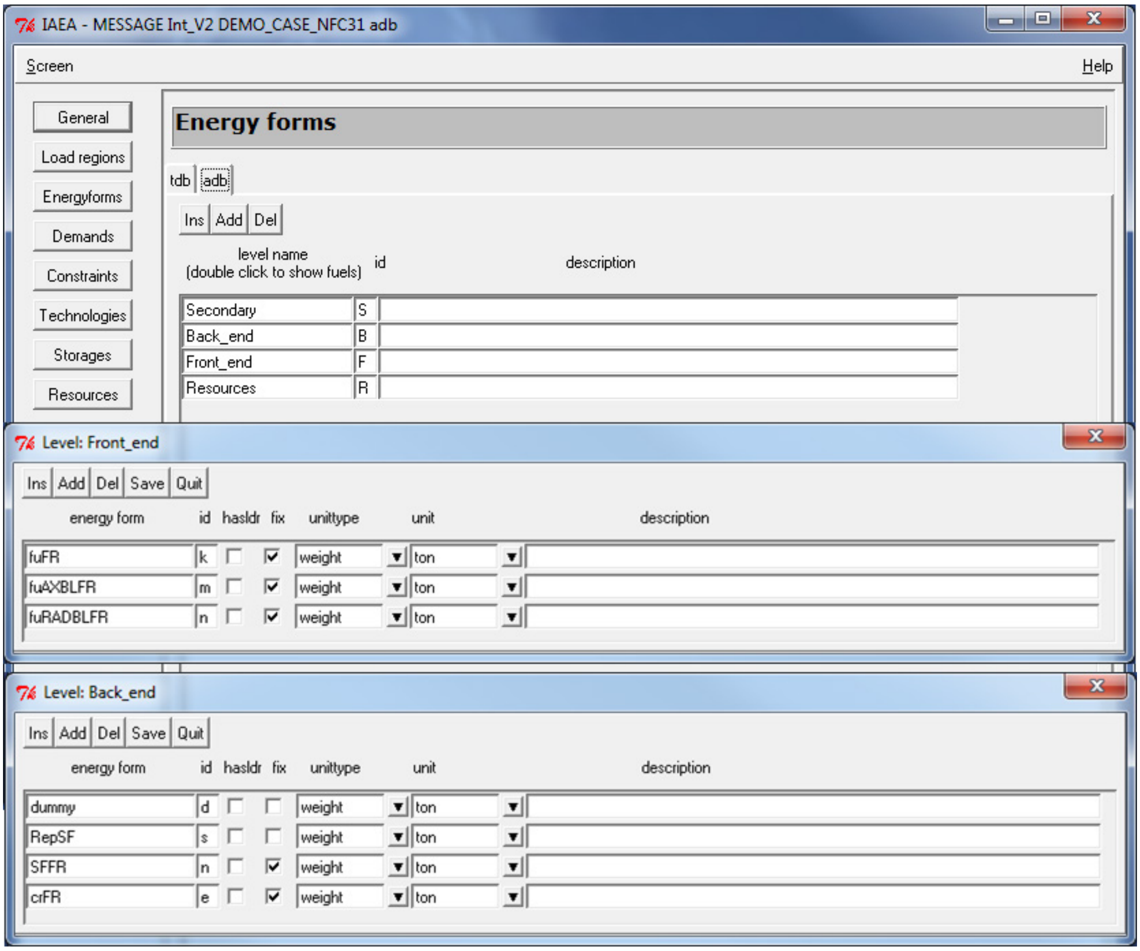


Level	Energyform	Producers	Consumers
Resources	Puextr		fuFR
Front_end	fuFR	fuFR	FR
	fuAXBLFR	fuAXBLFR	FR
	fuRADBLFR	fuRADBLFR	FR
Back_end	dummy	fcFR	
	RepSF	ReFR	
	SFFR	fsFR	ReFR
	crFR		fcFR
Secondary	Electricity	FR add	

FIG. 4.3. Energy and technology chain of a FR_MOX fuel cycle.

4.1.2. MESSAGE modelling of a closed fuel cycle with one unit of FR_MOX with plutonium multi-recycling (Demo_Case_NFC31)

Similar to previous cases, the fuel cycle model needs to be constructed step by step in MESSAGE. The general data screen remains the same, as the units are unchanged. In the energy forms screen (see Fig. 4.4), the back end and front end need to be redefined from the drop-down menu as shown in Fig. 4.3.



level name (double click to show fuels)	id	description
Secondary	S	
Back_end	B	
Front_end	F	
Resources	R	

Level: Front_end

energy form	id	hasldr	fix	unittype	unit	description
fuFR	k	☐	☑	weight	ton	
fuAXBLFR	m	☐	☑	weight	ton	
fuRADBLFR	n	☐	☑	weight	ton	

Level: Back_end

energy form	id	hasldr	fix	unittype	unit	description
dummy	d	☐	☐	weight	ton	
RepSF	s	☐	☐	weight	ton	
SFFR	n	☐	☑	weight	ton	
crFR	e	☐	☑	weight	ton	

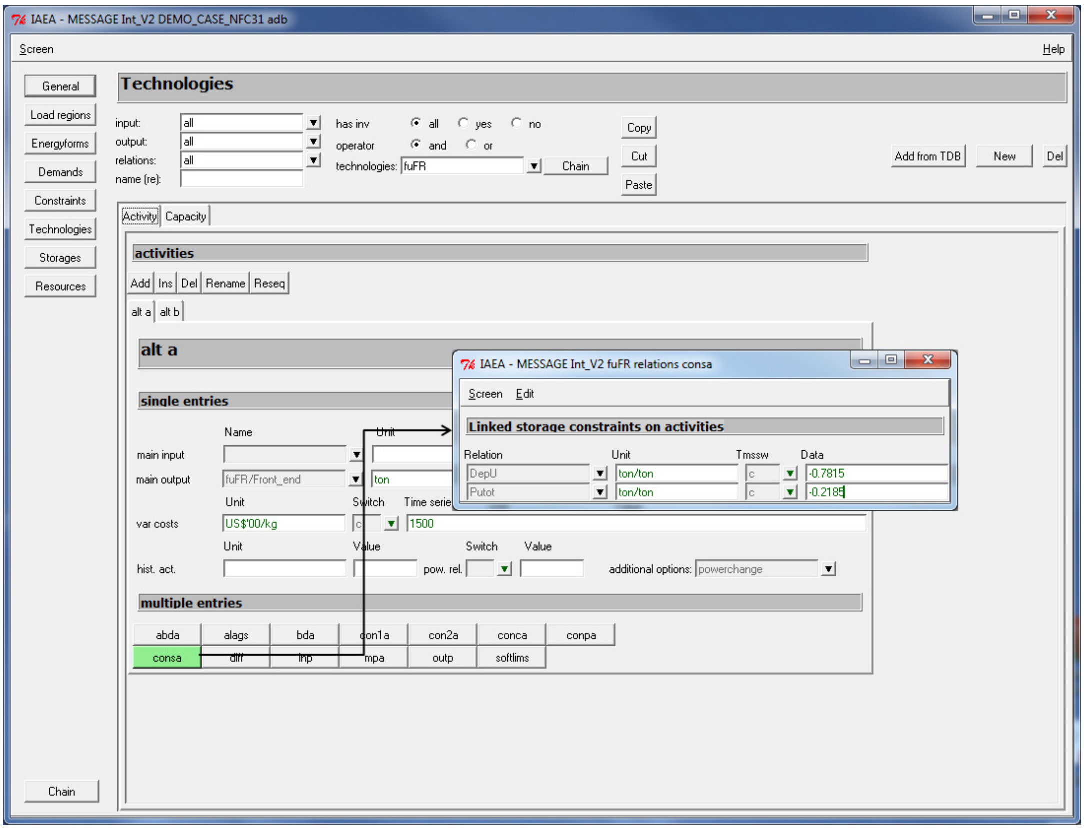
FIG. 4.4. Entering energy forms and unit type in the energy forms window.

For this case, technologies and storages to be defined include MOX fuel fabrication for the core, axial and radial blanket fuel fabrication for the FR_MOX reactor, reprocessing of MOX spent fuel, storages for depleted uranium, MOX spent fuel, and the reprocessing products uranium, minor actinides, plutonium, fission products and plutonium losses. The list of technology and storage is given in Table 4.6.

TABLE 4.6. TECHNOLOGY AND STORAGE USED FOR MODELLING A CLOSED FUEL CYCLE

Technology and storage	Explanation
fuFR	MOX core fuel fabrication technology
fuAXBLFR	Axial blanket fuel fabrication technology
fuRADBLFR	Radial blanket fuel fabrication technology
fuMOXLWR	MOX fuel fabrication technology
FR	Fast reactor using MOX fuel for the core and depleted uranium for the blankets
fcFR	Auxiliary technology fcFR technology puts spent fuel discharged from core and blankets after reactor shutdown to storage SFFR
fsFR	Auxiliary technology fsFR technology delivers unit of spent fuel for further processing
ReFR	Reprocessing technology
DepU	Depleted uranium storage
SFFR	Storage for UOX spent fuel including cooling and temporary storage
Pulosses	Storage for MOX spent fuel including cooling and temporary storage
Putot	Reprocessed plutonium stock
MAc	Reprocessed minor actinide stock
ReUL	Reprocessed uranium stock
FPr	Separated fission product storage

Figures 4.5 and 4.6 show the construction of MOX fuel fabrication technology fuFR. There are two alternatives in the activity screen: alt a is used for fuels from the reactor’s own reprocessed plutonium; alt b is used for MOX fuel from external plutonium. Fabrication of 1 t HM of MOX fuel requires 0.218 5 t HM of plutonium (see Table 4.1) and 0.781 5 t HM (= 1 − 0.218 5) of depleted uranium. In alt a, both values are negative, since they are taken from storages.



Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: fuFR

activities

alt a

single entries

	Name	Unit
main input		
main output	fuFR/Front_end	ton

	Unit	Switch	Time series
var costs	US$'00/kg	c	1500

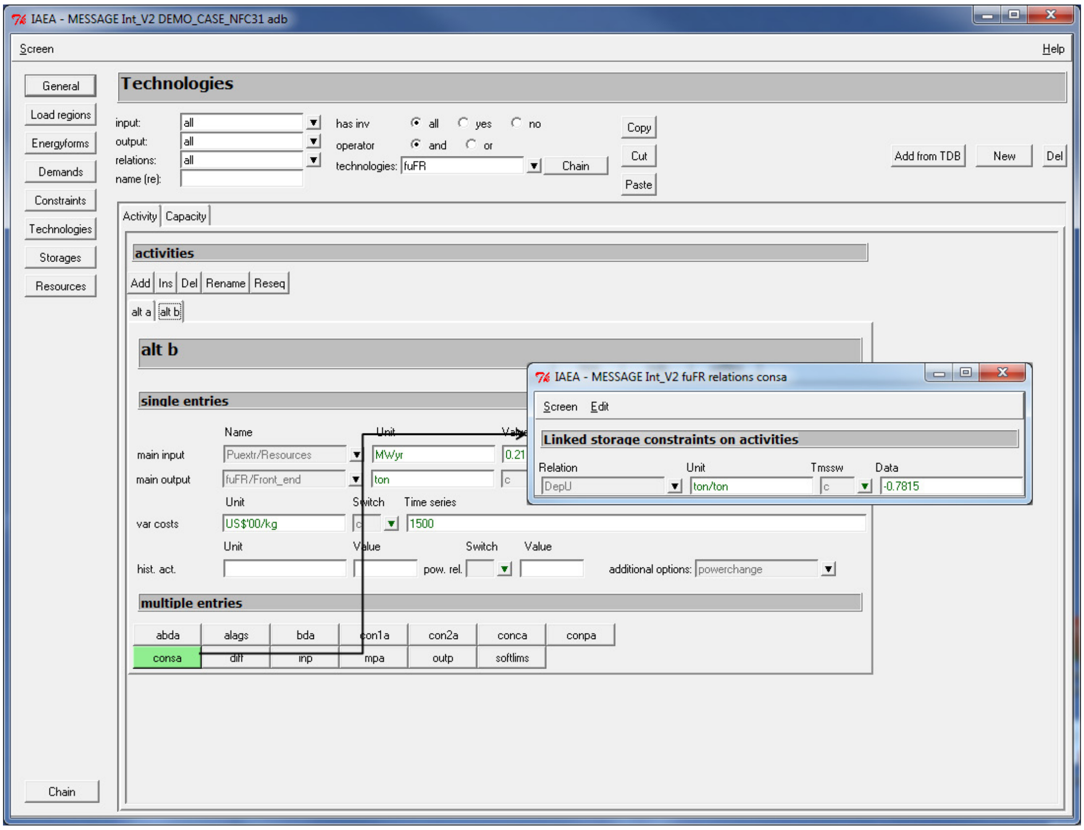
hist. act. Unit: Value: pow. rel. Switch: Value:
additional options: powerchange

multiple entries

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
DepU	ton/ton	c	-0.7815
Putot	ton/ton	c	-0.2185

FIG. 4.5. *MOX fuel fabrication technology fuFR alt a.*



Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: fuFR

activities

alt b

single entries

	Name	Unit	Value
main input	Puextr/Resources	MWyr	0.21
main output	fuFR/Front_end	ton	c

	Unit	Switch	Time series
var costs	US$'00/kg	c	1500

hist. act. Unit: Value: pow. rel. Switch: Value:
additional options: powerchange

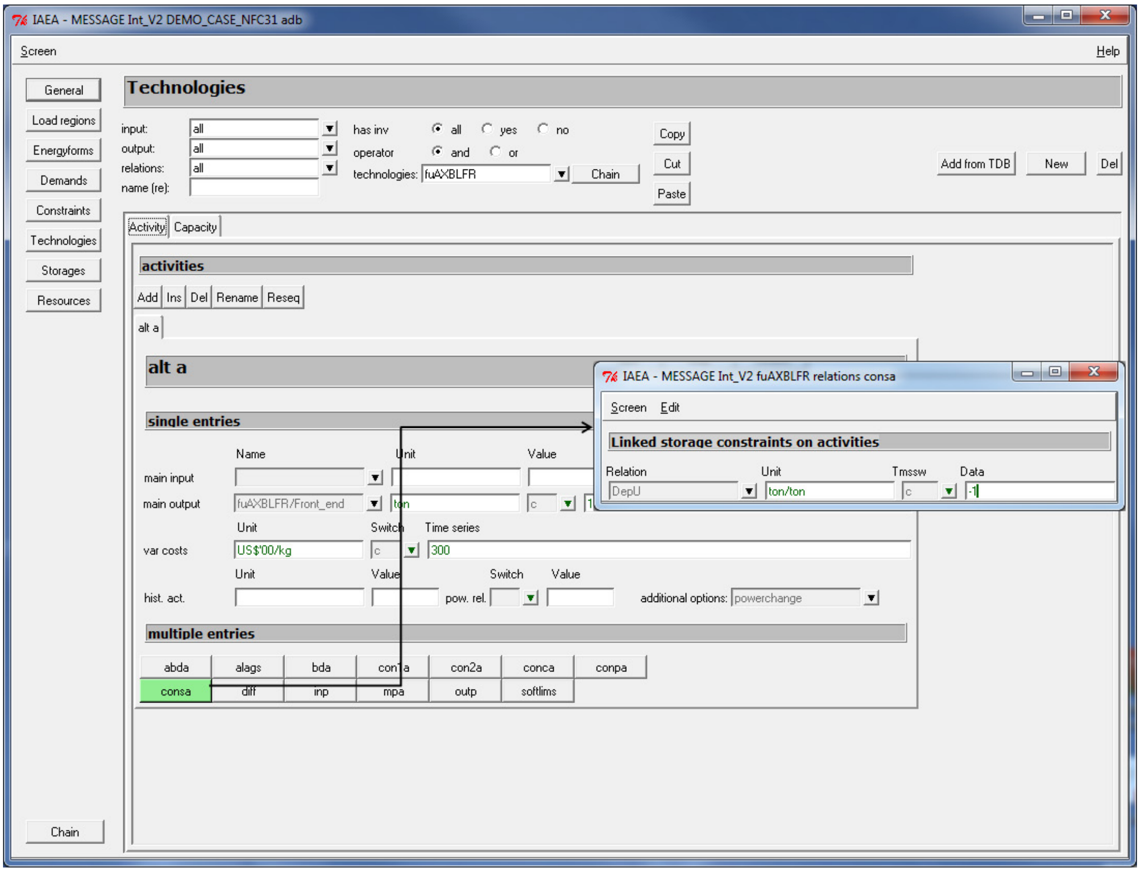
multiple entries

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
DepU	ton/ton	c	-0.7815

FIG. 4.6. *MOX fuel fabrication technology fuFR alt b.*

As shown in Fig. 4.7, the blanket fuel fabrication technology takes 1 t HM of depleted uranium from a depleted uranium storage to produce 1 t HM of fast reactor blanket fuel. Both axial and radial fast reactor blankets are loaded with depleted uranium, which comes from the enrichment process.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC31 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv: ● all ○ yes ○ no
operator: ● and ○ or
technologies: fuAXBLFR

activities

alt a

single entries

main output: fuAXBLFR/Front_end, Unit: ton, Switch: c, Value: 1
var costs: Unit: US$'00/kg, Switch: c, Time series: 300
additional options: powerchange

IAEA - MESSAGE Int_V2 fuAXBLFR relations consa

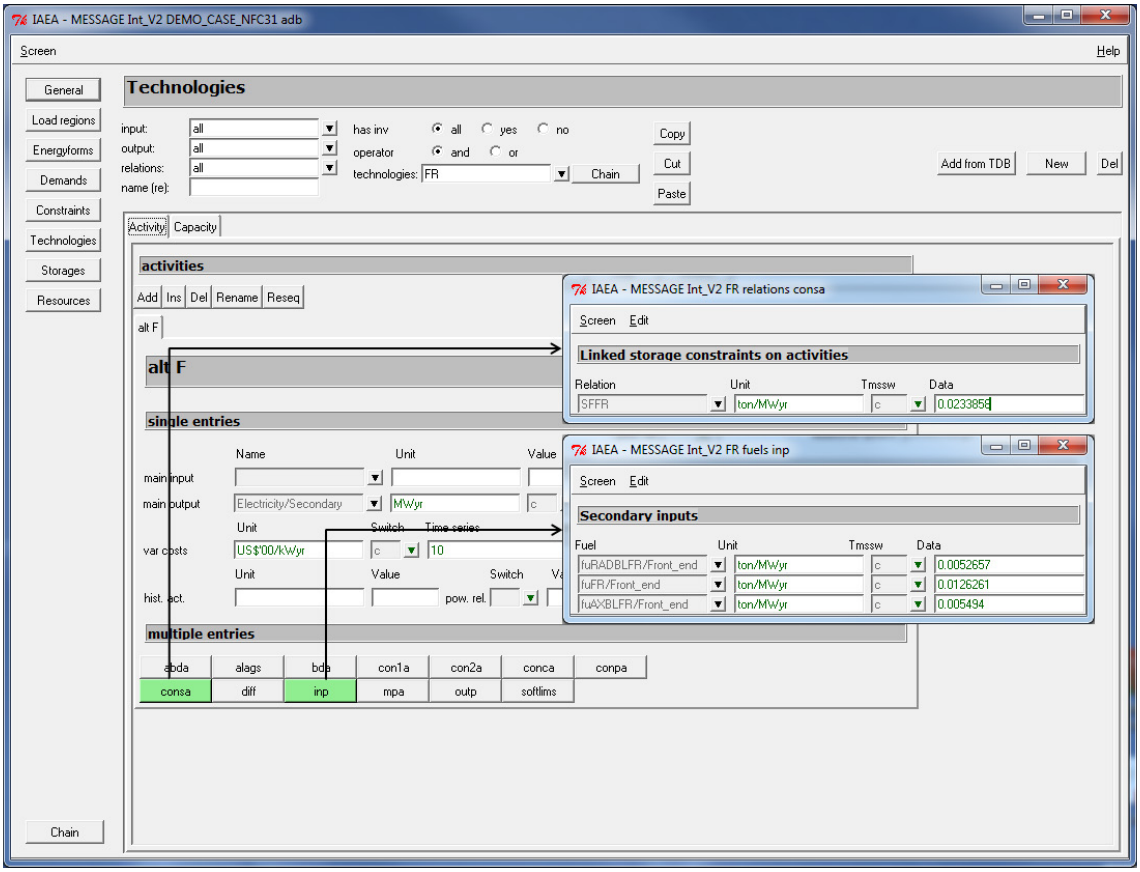
Linked storage constraints on activities

Relation	Unit	Tmssw	Data
DepU	ton/ton	c	-1

FIG. 4.7. *Axial blanket fuel fabrication technology.*

4.1.2.1. Reactor FR_MOX

The FR_MOX requires an annual consumption of 9.336 t HM of MOX fuel, 4.063 t HM of depleted uranium for the axial blanket and 3.894 t HM of depleted uranium for the radial blanket to produce 740 MW·a of electricity. It discharges a total of 17.294 t of mixed MOX and blanket spent fuel to storage. The ratio of fresh fuel consumed by the reactor to the unit of electricity output should be 0.012 6 (= 9.336/740) for MOX fuel, 0.005 49 (= 4.063/740) for the axial blanket fuel and 0.005 27 (≈ 3.894/740) for the radial blanket fuel. Fresh fuels are delivered by secondary input (see Fig. 4.8). All spent nuclear fuel (MOX and blankets) discharged from the reactor goes to the cooling storage SFFR. This can be calculated as the fraction of the unit amount of main output, which is 0.023 4 (= 17.294/740).



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC31 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: FR

alt F

main input
main output: Electricity/Secondary, MWyr, c
var costs: Unit US$'00/kWyr, Switch c, Time series 10
hist. act.
pow. rel.

IAEA - MESSAGE Int_V2 FR relations consa

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
SFFR	ton/MWyr	c	0.0233858

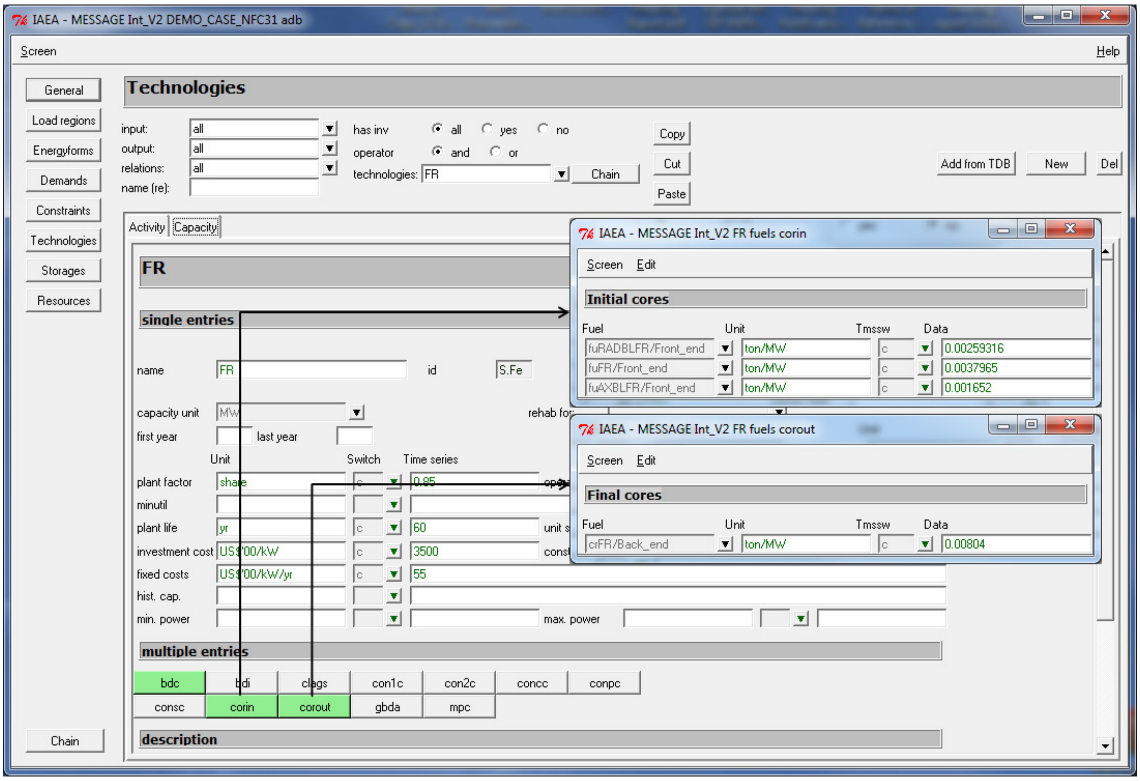
IAEA - MESSAGE Int_V2 FR fuels inp

Secondary inputs

Fuel	Unit	Tmssw	Data
fuRADBLFR/Front_end	ton/MWyr	c	0.0052657
fuFR/Front_end	ton/MWyr	c	0.0126261
fuAXBLFR/Front_end	ton/MWyr	c	0.005494

FIG. 4.8. Modelling FR_MOX reactor technology in the activity window.

The initial core loading and final core discharge data should be given as the fraction of the unit amount of reactor installed capacity. Two tabs labelled *corin* and *corout*, at the bottom part of the *Capacity* tab in the technologies window, are for the initial core loading and final core discharge, respectively (see Fig. 4.9). FR_MOX installed capacity is 870 MW(e), while initial core loading is 12.6 t HM for MOX fuel, 5.5 t HM for the axial blanket fuel and 6.2 t HM for the radial blanket fuel (see Table 4.1). It follows that the corresponding specific values in *corin* are 0.003 80 (≈ (12.6 − 9.336)/870) for MOX fuel, 0.001 65 (= (5.5 − 4.063)/870) for the axial blanket fuel and 0.002 59 (≈ (6.2 − 3.894)/870) for the radial blanket fuel. The final core unloading (including fission products) is the sum of first core and blankets loading, therefore the specific value in *corout* is 0.008 04 (= (24.29 − 17.294)/870).



Technologies

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: FR

FR

name: FR
id: S.Fe
capacity unit: MW
first year:
last year:

	Unit	Switch	Time series
plant factor	share	c	0.85
minutil			
plant life	yr	c	60
investment cost	US$'00/kW	c	3500
fixed costs	US$'00/kW/yr	c	55
hist. cap.			
min. power			

max. power:

IAEA - MESSAGE Int_V2 FR fuels corin

Screen Edit

Initial cores

Fuel	Unit	Tmssw	Data
fuRADBLFR/Front_end	ton/MW	c	0.00259316
fuFR/Front_end	ton/MW	c	0.0037965
fuAXBLFR/Front_end	ton/MW	c	0.001652

IAEA - MESSAGE Int_V2 FR fuels corout

Screen Edit

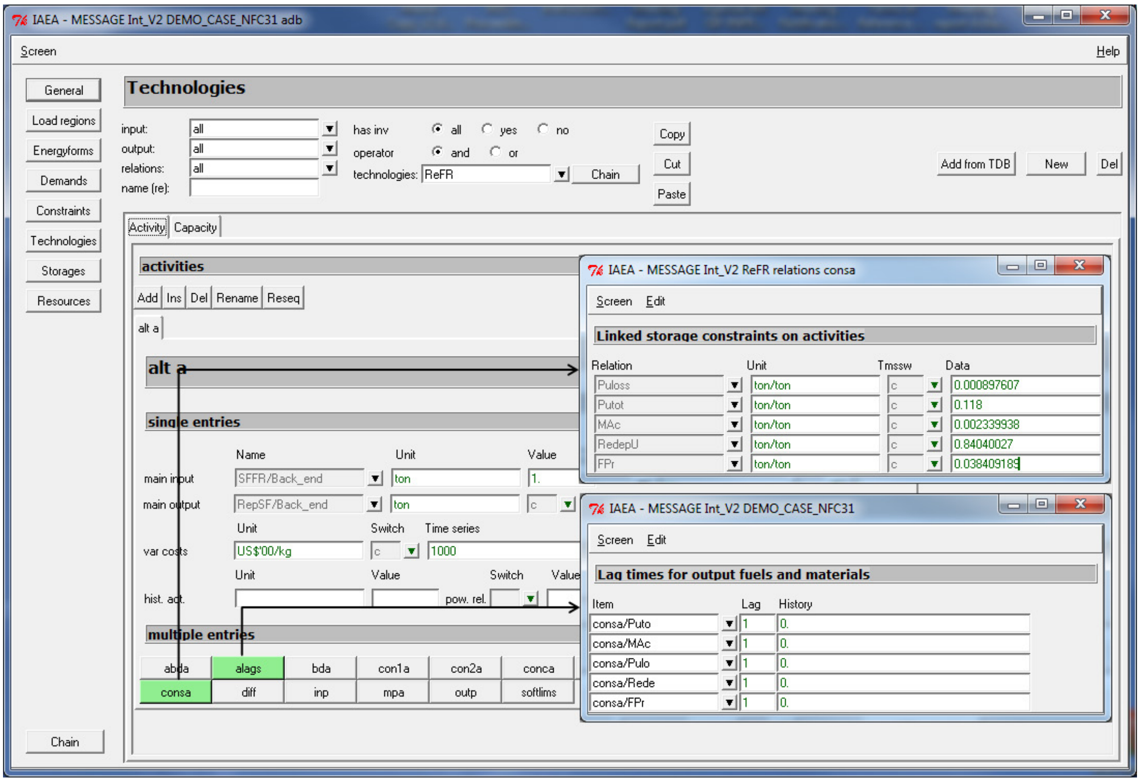
Final cores

Fuel	Unit	Tmssw	Data
crFR/Back_end	ton/MW	c	0.00804

FIG. 4.9. Modelling FR_MOX reactor technology in the capacity window.

4.1.2.2. Reprocessing technology ReFR

The fuel discharged from the core and the blankets are reprocessed together. The nuclide group composition from all mixed spent fuel after two years cooling and one year reprocessing is given in Table 4.2. Reprocessing technology can be modelled as in Fig. 4.10, taking one unit of spent fuel and putting to storage 0.840 of uranium, 0.118 of plutonium, 0.002 34 of minor actinides and 0.038 4 of fission products, while 0.000 898 of plutonium goes to losses. The main output has an auxiliary role and puts one unit of spent fuel to the dummy level. A lag time (one year) in reprocessing operations is entered in the tab labelled *alags*, in the activity window.



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC31 adb

input: all
output: all
relations: all
name (re):
has inv ● all ○ yes ○ no
operator ● and ○ or
technologies: ReFR

	Name	Unit	Value
main input	SFFR/Back_end	ton	1.
main output	RepSF/Back_end	ton	c

	Unit	Switch	Time series
var costs	US$'00/kg	c	1000

	Unit	Value	pow. rel. Switch	Value
hist. act.				

IAEA - MESSAGE Int_V2 ReFR relations consa

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
Puloss	ton/ton	c	0.000897607
Putot	ton/ton	c	0.118
MAc	ton/ton	c	0.002339938
RedepU	ton/ton	c	0.84040027
FPr	ton/ton	c	0.038409189

IAEA - MESSAGE Int_V2 DEMO_CASE_NFC31

Lag times for output fuels and materials

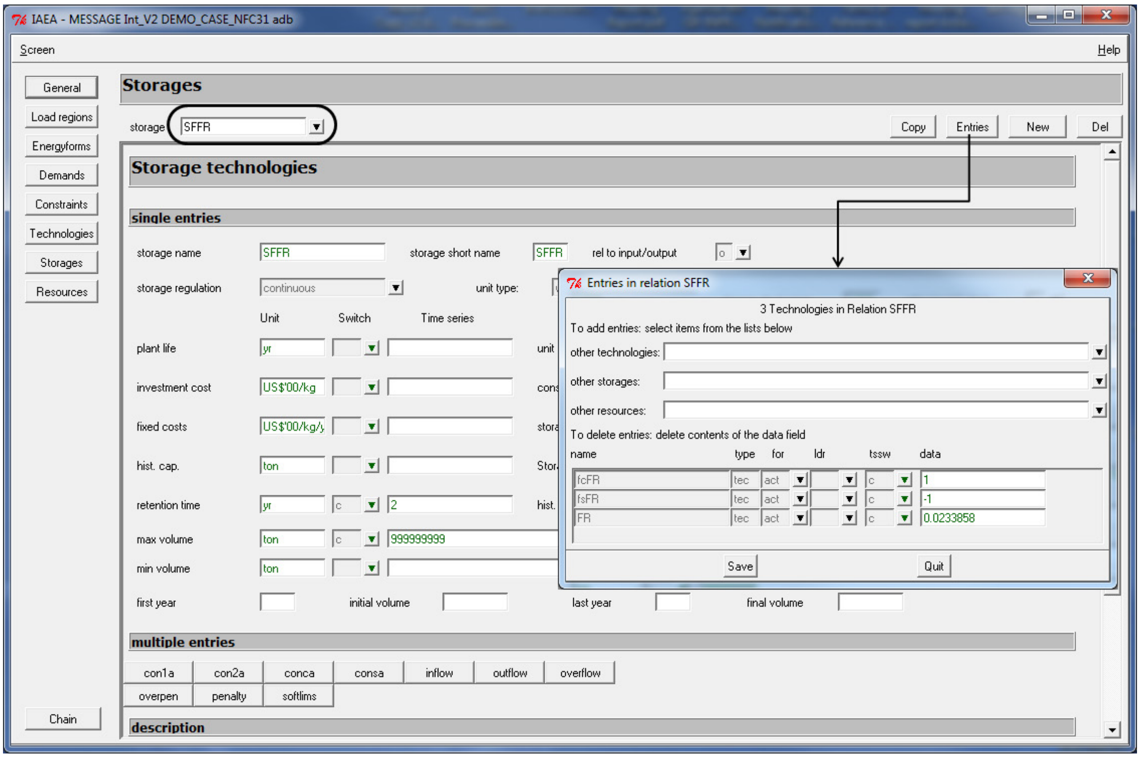
Item	Lag	History
consa/Puto	1	0.
consa/MAc	1	0.
consa/Pulo	1	0.
consa/Rede	1	0.
consa/FPr	1	0.

FIG. 4.10. Modelling reprocessing technology ReFR in the activity window.

After reprocessing, reprocessed products are delivered to related storages. In this example, there are seven storages for (see Fig. 4.11):

(a) Depleted uranium;
(b) Spent fuel;
(c) Reprocessed plutonium;
(d) Minor actinides;
(e) Fission products;
(f) Plutonium losses.

Figure 4.11 shows the modelling of the total discharged spent fuel for the core and blankets. The cooling time (two years) is entered in the retention time field within the storage technologies window. After cooling time, spent fuel can be moved to interim storage. For simplicity, the storages are modelled as one storage.



storage: SFFR

storage name: SFFR
storage short name: SFFR
rel to input/output: o
storage regulation: continuous
plant life: yr
investment cost: US$'00/kg
fixed costs: US$'00/kg/y
hist. cap.: ton
retention time: yr, c, 2
max volume: ton, c, 999999999
min volume: ton
first year:
initial volume:
last year:
final volume:

Entries in relation SFFR

3 Technologies in Relation SFFR

To add entries: select items from the lists below
other technologies:
other storages:
other resources:
To delete entries: delete contents of the data field

name	type	for	ldr	tssw	data
fcFR	tec	act		c	1
fsFR	tec	act		c	-1
FR	tec	act		c	0.0233858

FIG. 4.11. Modelling fast reactor spent fuel storage.

The tab labelled *Entries* is used to link technologies. SFFR storage, for example, has links with three technologies. Fast reactor technology puts 0.023 4 (= 17.29/740) of the total spent nuclear fuel (MOX and blankets) discharged from the reactor into cooling storage SFFR. These values can be entered in *Entries* or in the technology tab labelled *consa* (see Fig. 4.8). Furthermore, fcFR technology puts spent fuel discharged from core and blankets after reactor shutdown, and fsFR technology takes spent fuel for further processing.

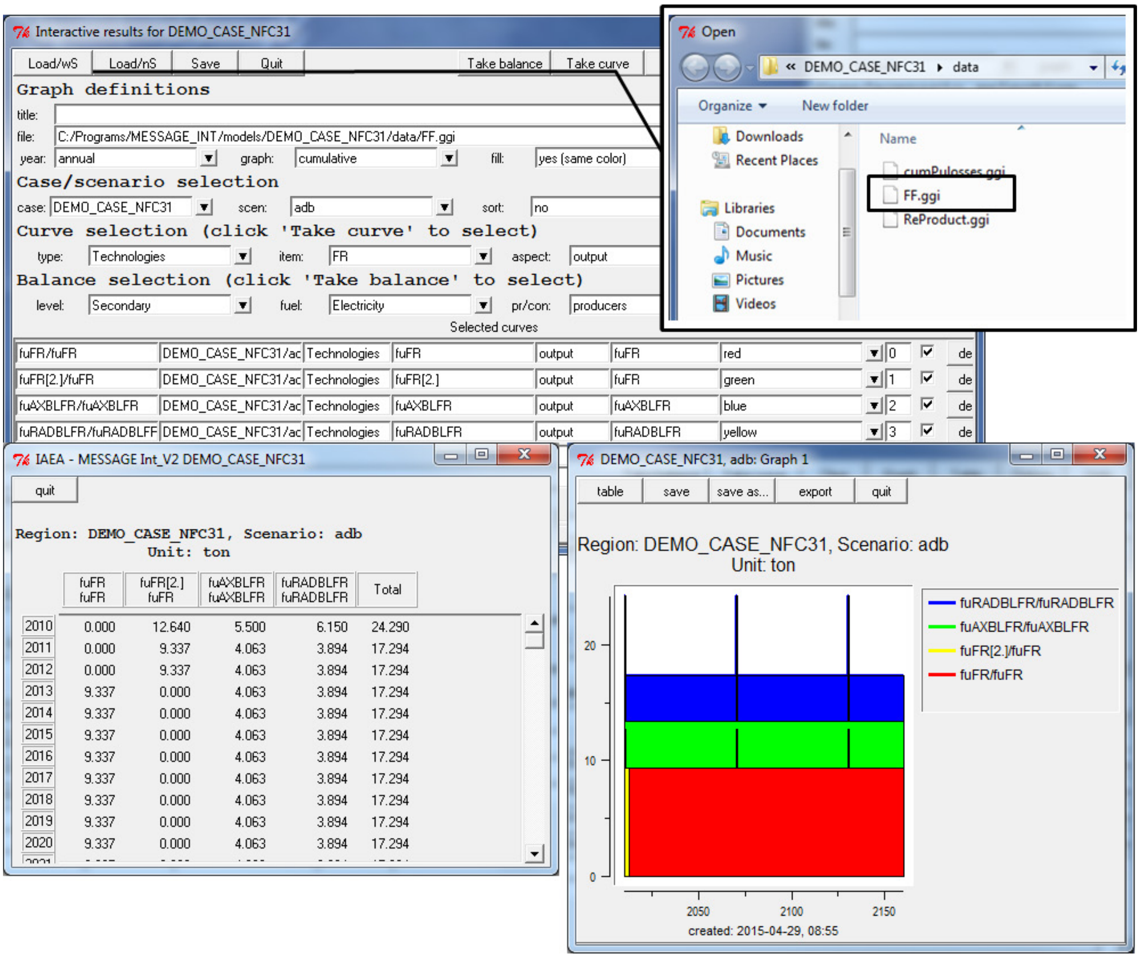
4.1.3. Mass flow MESSAGE outputs for a closed fuel cycle with one unit of FR_MOX with plutonium multi-recycling

After running MESSAGE Demo_Case_NFC3, the mass flow result can be displayed in the interactive mode and compared with analytical calculations. The selected and saved results are in Table 4.7. Results can be reloaded using the tab labelled *Load/ws*.

TABLE 4.7. SELECTED MASS FLOW OUTPUTS FOR A CLOSED FUEL CYCLE

File name of results, selected and saved	Explanation
FF.ggi	Fresh fuel requirements (core and blankets)
ReProduct.ggi	Reprocessed products (plutonium, minor actinides, uranium and fission products)
cumPulosses.ggi	Accumulation of plutonium losses

According to analytical calculations, a FR_MOX reactor consumes 9.337 t HM of MOX fuel for the core and 4.063 t HM and 3.894 t HM for the blankets (axial and radial, respectively). The first loadings in the core and blankets are 12.64 t HM, 5.50 t HM and 6.15 t HM, respectively. Outputs from fuel fabrication technology display the data in Fig. 4.12, where it can be observed that the fuel for first loading and two year operations is fabricated from external plutonium. Afterwards, the reactor operates in self-sufficient mode and consumes fuel fabricated from its own reprocessed plutonium.



Graph definitions

title:
file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC31/data/FF.ggi
year: annual ▾ graph: cumulative ▾ fill: yes (same color)

Case/scenario selection

case: DEMO_CASE_NFC31 ▾ scen: adb ▾ sort: no

Curve selection (click 'Take curve' to select)

type: Technologies ▾ item: FR ▾ aspect: output

Balance selection (click 'Take balance' to select)

level: Secondary ▾ fuel: Electricity ▾ pr/con: producers

Selected curves

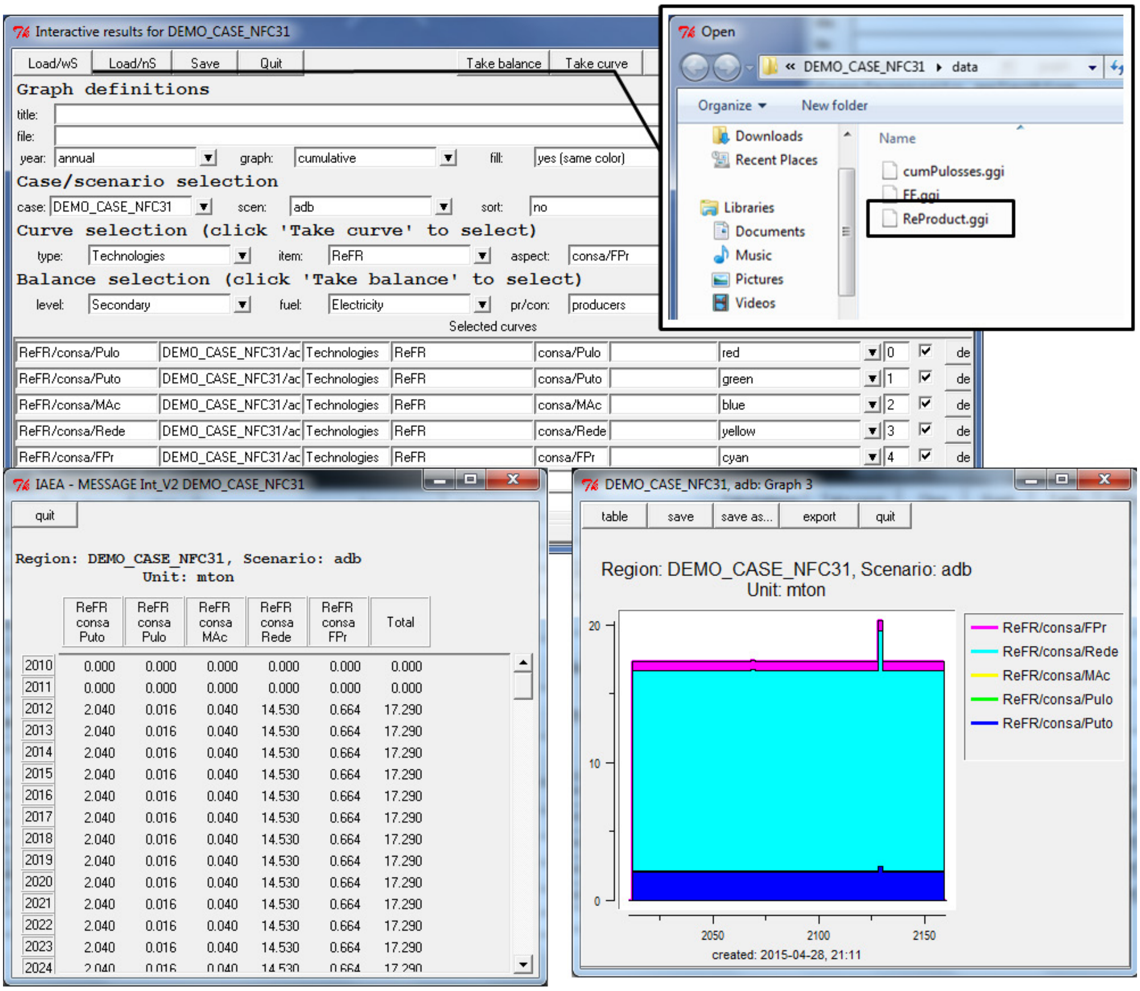
fuFR/fuFR	DEMO_CASE_NFC31/ac	Technologies	fuFR	output	fuFR	red ▾	0	☑	de
fuFR[2.]/fuFR	DEMO_CASE_NFC31/ac	Technologies	fuFR[2.]	output	fuFR	green ▾	1	☑	de
fuAXBLFR/fuAXBLFR	DEMO_CASE_NFC31/ac	Technologies	fuAXBLFR	output	fuAXBLFR	blue ▾	2	☑	de
fuRADBLFR/fuRADBLFF	DEMO_CASE_NFC31/ac	Technologies	fuRADBLFR	output	fuRADBLFR	yellow ▾	3	☑	de

Region: DEMO_CASE_NFC31, Scenario: adb
Unit: ton

	fuFR fuFR	fuFR[2.] fuFR	fuAXBLFR fuAXBLFR	fuRADBLFR fuRADBLFR	Total
2010	0.000	12.640	5.500	6.150	24.290
2011	0.000	9.337	4.063	3.894	17.294
2012	0.000	9.337	4.063	3.894	17.294
2013	9.337	0.000	4.063	3.894	17.294
2014	9.337	0.000	4.063	3.894	17.294
2015	9.337	0.000	4.063	3.894	17.294
2016	9.337	0.000	4.063	3.894	17.294
2017	9.337	0.000	4.063	3.894	17.294
2018	9.337	0.000	4.063	3.894	17.294
2019	9.337	0.000	4.063	3.894	17.294
2020	9.337	0.000	4.063	3.894	17.294

FIG. 4.12. Fresh fuel requirements (core and blankets).

Reprocessing of 17.29 t of spent fuel produces 14.53 t HM of uranium, 2.040 t HM of reprocessed plutonium, 0.016 t HM of plutonium losses, 0.040 t HM of minor actinides, 0.664 t of fission products (see Table 4.5). The data are extracted from consa of reprocessed technology ReFR (see Fig. 4.13).



Graph definitions

title:
file:
year: annual
graph: cumulative
fill: yes (same color)

Case/scenario selection

case: DEMO_CASE_NFC31
scen: adb
sort: no

Curve selection (click 'Take curve' to select)

type: Technologies
item: ReFR
aspect: consa/FPr

Balance selection (click 'Take balance' to select)

level: Secondary
fuel: Electricity
pr/con: producers

Selected curves

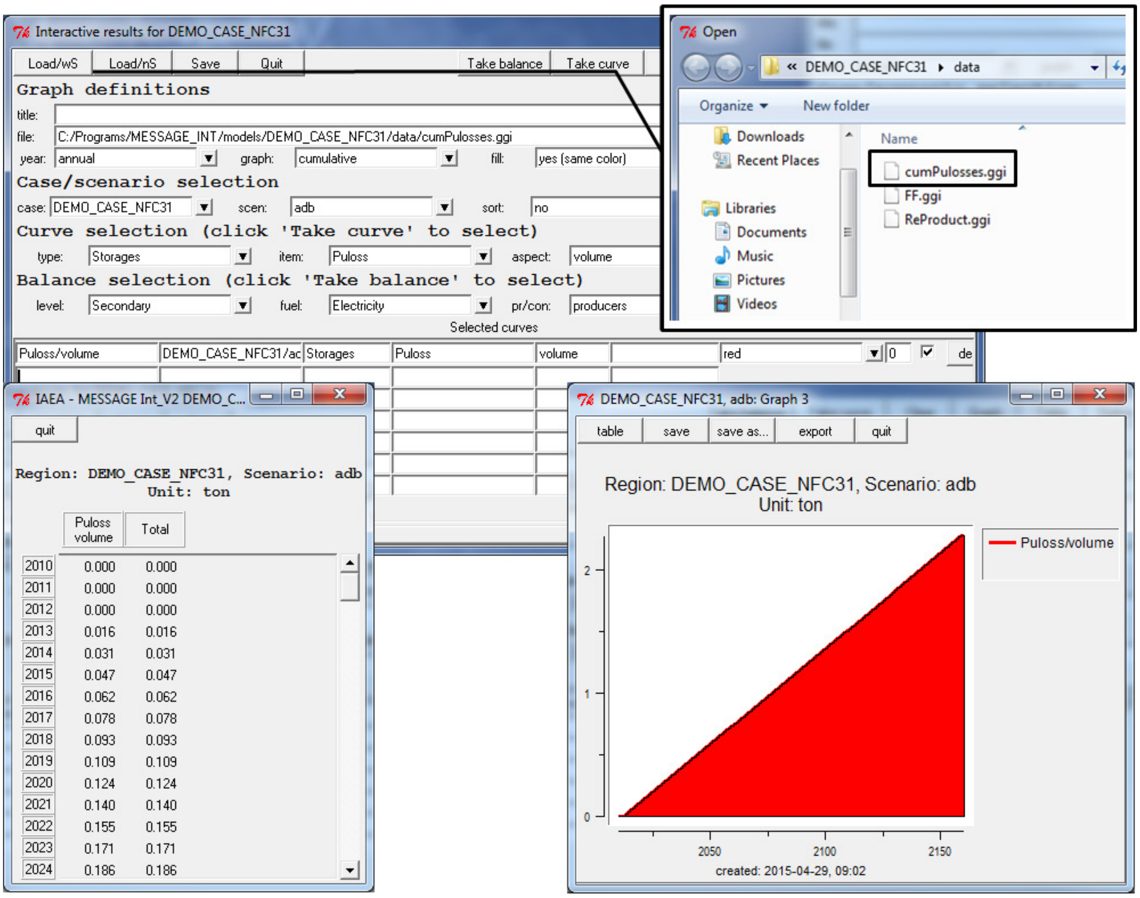
ReFR/consa/Pulo	DEMO_CASE_NFC31/ac	Technologies	ReFR	consa/Pulo		red	0	☑	de
ReFR/consa/Puto	DEMO_CASE_NFC31/ac	Technologies	ReFR	consa/Puto		green	1	☑	de
ReFR/consa/MAc	DEMO_CASE_NFC31/ac	Technologies	ReFR	consa/MAc		blue	2	☑	de
ReFR/consa/Rede	DEMO_CASE_NFC31/ac	Technologies	ReFR	consa/Rede		yellow	3	☑	de
ReFR/consa/FPr	DEMO_CASE_NFC31/ac	Technologies	ReFR	consa/FPr		cyan	4	☑	de

Region: DEMO_CASE_NFC31, Scenario: adb
Unit: mton

	ReFR consa Puto	ReFR consa Pulo	ReFR consa MAc	ReFR consa Rede	ReFR consa FPr	Total
2010	0.000	0.000	0.000	0.000	0.000	0.000
2011	0.000	0.000	0.000	0.000	0.000	0.000
2012	2.040	0.016	0.040	14.530	0.664	17.290
2013	2.040	0.016	0.040	14.530	0.664	17.290
2014	2.040	0.016	0.040	14.530	0.664	17.290
2015	2.040	0.016	0.040	14.530	0.664	17.290
2016	2.040	0.016	0.040	14.530	0.664	17.290
2017	2.040	0.016	0.040	14.530	0.664	17.290
2018	2.040	0.016	0.040	14.530	0.664	17.290
2019	2.040	0.016	0.040	14.530	0.664	17.290
2020	2.040	0.016	0.040	14.530	0.664	17.290
2021	2.040	0.016	0.040	14.530	0.664	17.290
2022	2.040	0.016	0.040	14.530	0.664	17.290
2023	2.040	0.016	0.040	14.530	0.664	17.290
2024	2.040	0.016	0.040	14.530	0.664	17.290

FIG. 4.13. Reprocessed products (plutonium, minor actinides, uranium and fission products).

Each year 0.016 t HM of plutonium losses is put to storage. Plutonium losses accumulation is displayed in Fig. 4.14.



Graph definitions

title:

file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC31/data/cumPulosses.ggi

year: annual graph: cumulative fill: yes (same color)

Case/scenario selection

case: DEMO_CASE_NFC31 scen: adb sort: no

Curve selection (click 'Take curve' to select)

type: Storages item: Puloss aspect: volume

Balance selection (click 'Take balance' to select)

level: Secondary fuel: Electricity pr/con: producers

Selected curves

Puloss/volume DEMO_CASE_NFC31/ac Storages Puloss volume red 0 ☑ de

Region: DEMO_CASE_NFC31, Scenario: adb
Unit: ton

	Puloss volume	Total
2010	0.000	0.000
2011	0.000	0.000
2012	0.000	0.000
2013	0.016	0.016
2014	0.031	0.031
2015	0.047	0.047
2016	0.062	0.062
2017	0.078	0.078
2018	0.093	0.093
2019	0.109	0.109
2020	0.124	0.124
2021	0.140	0.140
2022	0.155	0.155
2023	0.171	0.171
2024	0.186	0.186

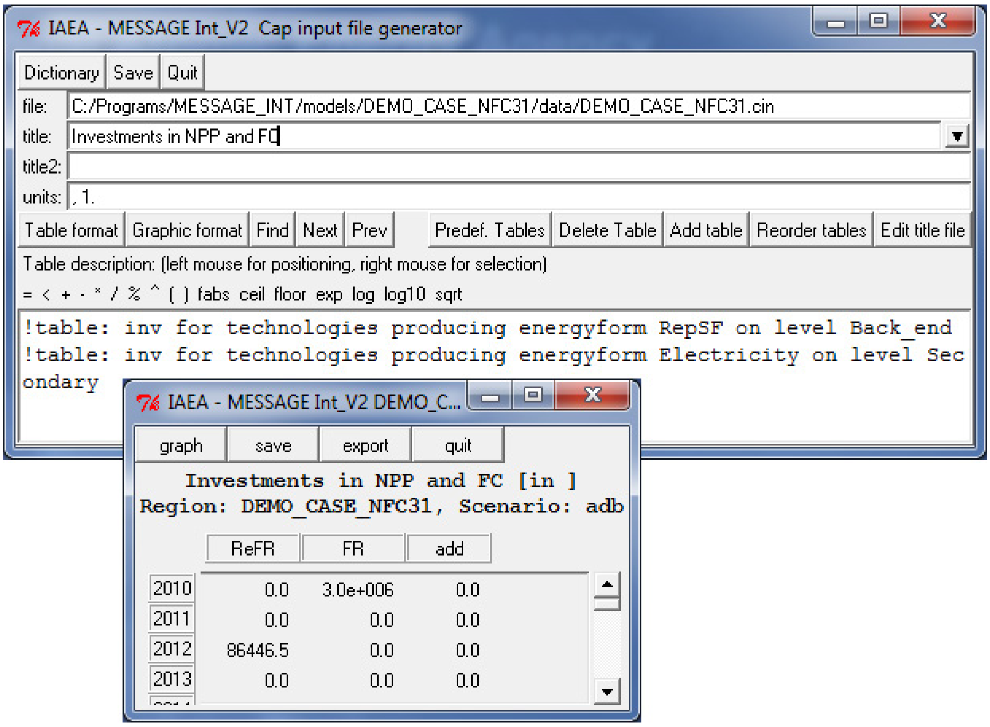
FIG. 4.14. Accumulation of plutonium losses.

4.1.4. Economic results of MESSAGE modelling for a closed fuel cycle with one unit of FR_MOX and plutonium multi-recycling

The economic results are extracted through a cin file, prepared in the same way as in Demo_Case_NFC1. Three tables were prepared to calculate the following results:

- Annual investments in the NPP;
- Annual expenditure on the total fuel cycle and O&M of the NPP;
- LUAC&LUOM.

Annual investments in the NPP are displayed in Fig. 4.15, as prepared with the tab *Predef. Tables*. Investment costs for technologies producing energy form electricity at the secondary level were selected. Investments and other costs are measured by multiplying US \$1000 to the capacity, since capacity has the unit MW and overnight cost has the unit US \$/kW (MW·US \$/kW = US \$1000). The table in Fig. 4.15 displays annual investment in FR_MOX as US \$3 billion in 2010 (= 3 × 10^6 × US \$1000), while the reprocessing plant cost US \$86.4 million in 2012 (= 86 447 in US \$1000).



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC31/data/DEMO_CASE_NFC31.cin
title: Investments in NPP and FC
title2:
units: , 1.

Table description: (left mouse for positioning, right mouse for selection)
= < + - * / % ^ ( ) fabs ceil floor exp log log10 sqrt

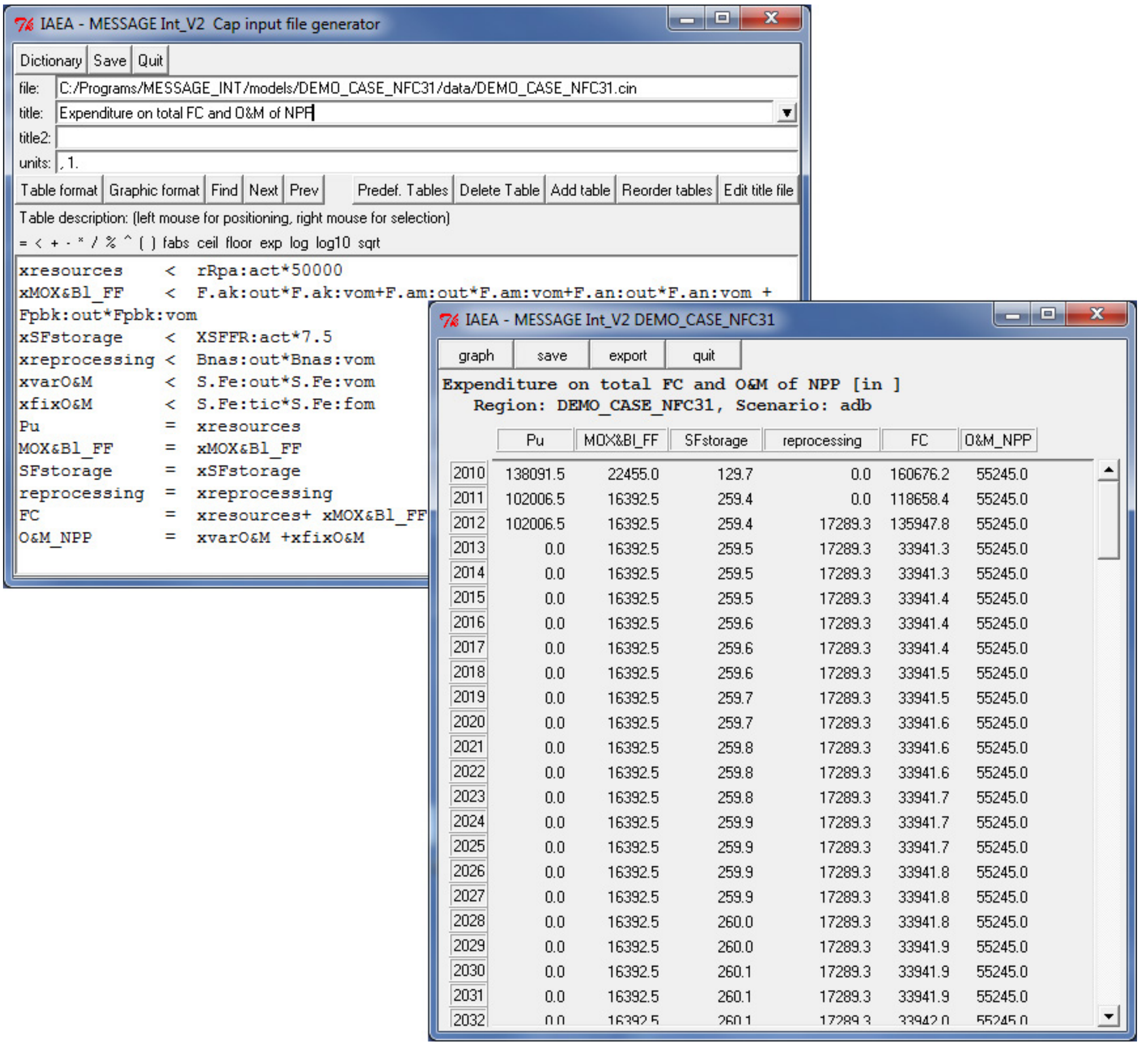
```
!table: inv for technologies producing energyform RepSF on level Back_end
!table: inv for technologies producing energyform Electricity on level Sec
ondary
```

```
  Investments in NPP and FC [in ]
Region: DEMO_CASE_NFC31, Scenario: adb

          ReFR       FR        add
2010       0.0    3.0e+006     0.0
2011       0.0       0.0       0.0
2012   86446.5       0.0       0.0
2013       0.0       0.0       0.0
```

FIG. 4.15. Annual investments in the NPP.

Annual expenditure on the fuel cycle and O&M of the NPP is given in Fig. 4.16. Expenditure has been calculated for the fuel cycle, including plutonium, MOX+blanket fresh fuel fabrication, O&M of reprocessing and spent fuel storage. Expenditure for each fuel cycle step can be obtained by multiplying the amount of material for a given step by its corresponding specific cost. Resulting calculations are listed in the table on the right. Annual expenditure on O&M of the NPP (fixed and variable O&M) was also included, with costs and investment measured in thousands of US dollars. LUAC&LUOM for a fast reactor was prepared with the help of the tab labelled *Predef. Tables*. The result is US $256.7/kW·a.



file: C:/Programs/MESSAGE_INT/models/DEMO_CASE_NFC31/data/DEMO_CASE_NFC31.cin

title: Expenditure on total FC and O&M of NPP

title2:

units: , 1.

Table description: (left mouse for positioning, right mouse for selection)

```
xresources    <  rRpa:act*50000
xMOX&Bl_FF    <  F.ak:out*F.ak:vom+F.am:out*F.am:vom+F.an:out*F.an:vom +
Fpbk:out*Fpbk:vom
xSFstorage    <  XSFFR:act*7.5
xreprocessing <  Bnas:out*Bnas:vom
xvarO&M       <  S.Fe:out*S.Fe:vom
xfixO&M       <  S.Fe:tic*S.Fe:fom
Pu            =  xresources
MOX&Bl_FF     =  xMOX&Bl_FF
SFstorage     =  xSFstorage
reprocessing  =  xreprocessing
FC            =  xresources+ xMOX&Bl_FF
O&M_NPP       =  xvarO&M +xfixO&M
```

Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC31, Scenario: adb

	Pu	MOX&Bl_FF	SFstorage	reprocessing	FC	O&M_NPP
2010	138091.5	22455.0	129.7	0.0	160676.2	55245.0
2011	102006.5	16392.5	259.4	0.0	118658.4	55245.0
2012	102006.5	16392.5	259.4	17289.3	135947.8	55245.0
2013	0.0	16392.5	259.5	17289.3	33941.3	55245.0
2014	0.0	16392.5	259.5	17289.3	33941.3	55245.0
2015	0.0	16392.5	259.5	17289.3	33941.4	55245.0
2016	0.0	16392.5	259.6	17289.3	33941.4	55245.0
2017	0.0	16392.5	259.6	17289.3	33941.4	55245.0
2018	0.0	16392.5	259.6	17289.3	33941.5	55245.0
2019	0.0	16392.5	259.7	17289.3	33941.5	55245.0
2020	0.0	16392.5	259.7	17289.3	33941.6	55245.0
2021	0.0	16392.5	259.8	17289.3	33941.6	55245.0
2022	0.0	16392.5	259.8	17289.3	33941.6	55245.0
2023	0.0	16392.5	259.8	17289.3	33941.7	55245.0
2024	0.0	16392.5	259.9	17289.3	33941.7	55245.0
2025	0.0	16392.5	259.9	17289.3	33941.7	55245.0
2026	0.0	16392.5	259.9	17289.3	33941.8	55245.0
2027	0.0	16392.5	259.9	17289.3	33941.8	55245.0
2028	0.0	16392.5	260.0	17289.3	33941.8	55245.0
2029	0.0	16392.5	260.0	17289.3	33941.9	55245.0
2030	0.0	16392.5	260.1	17289.3	33941.9	55245.0
2031	0.0	16392.5	260.1	17289.3	33941.9	55245.0
2032	0.0	16392.5	260.1	17289.3	33942.0	55245.0

FIG. 4.16. Annual expenditure on the fuel cycle and O&M of the NPP.

4.2. A GLOBAL NES BASED ON THERMAL AND FAST REACTORS WITH THE RECYCLING OF PLUTONIUM RECOVERED FROM AN LWR AND MULTIPLE RECYCLING OF PLUTONIUM RECOVERED FROM A FAST REACTOR

The MESSAGE model illustrates the application of MESSAGE for modelling an NES based on thermal and fast reactors with plutonium multi-recycling. The reactors and fuels considered for this scenario are:

- An HWR using natural uranium fuel;
- An LWR using UOX fuel;
- An ALWR using UOX fuel;
- A fast reactor using MOX fuels for the core and depleted uranium for the blankets.

The timeframe considered is 2009–2160. The calculation conditions and thermal reactor data are the same as the global MESSAGE model for NFC1:

(a) Fast reactors are introduced in 2020;
(b) From 2021 to 2030, electricity production increases by 1 GW·a per fast reactor each year and achieves 10 GW·a in 2030;
(c) From 2031 to 2050, electricity production increases to 19.5 GW·a per fast reactor each year and achieves 400 GW·a in 2050.

After 2050, fast reactors are introduced according to plutonium availability and economic expediency. The scheme of this nuclear fuel cycle is presented in Fig. 4.17.

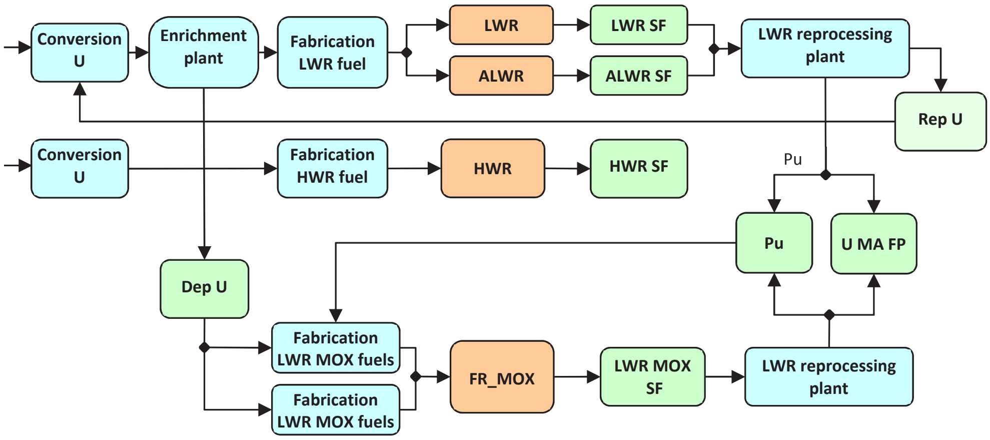
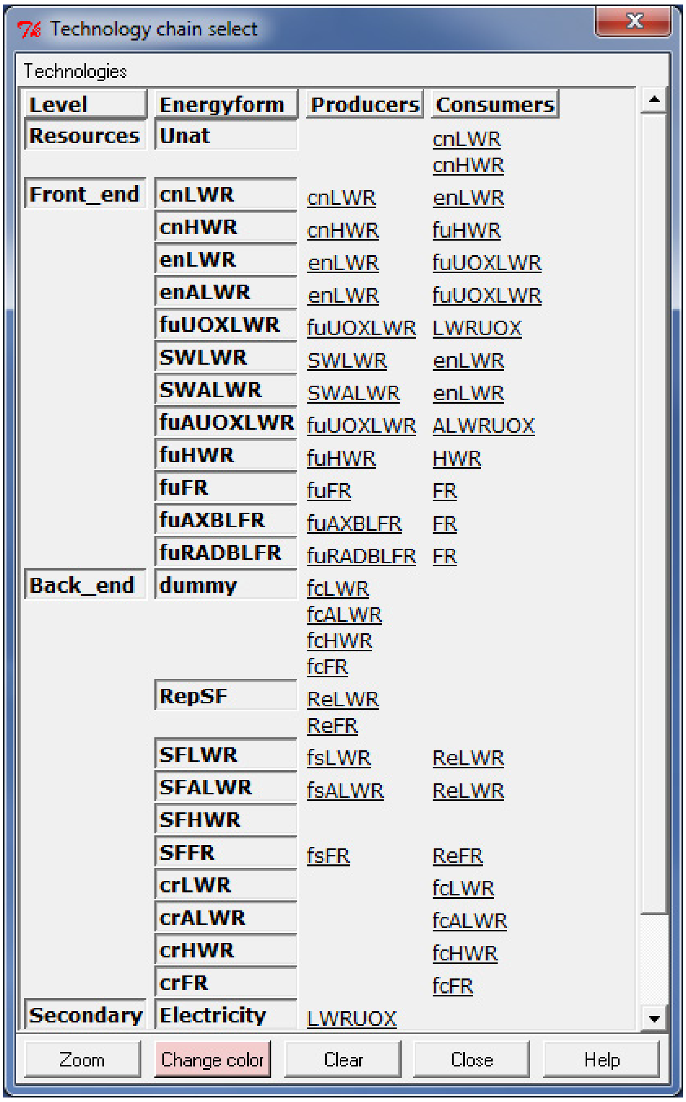


FIG. 4.17. Scheme of a global NES based on thermal and fast reactors.

The nuclide group composition of mixed MOX+blanket spent fuel was used for calculations of reprocessed products, with two years cooling and one year reprocessing. The decay of unstable isotopes in interim storage (prior to reprocessing) and the decay of plutonium and minor actinides in stock have not been taken into account.

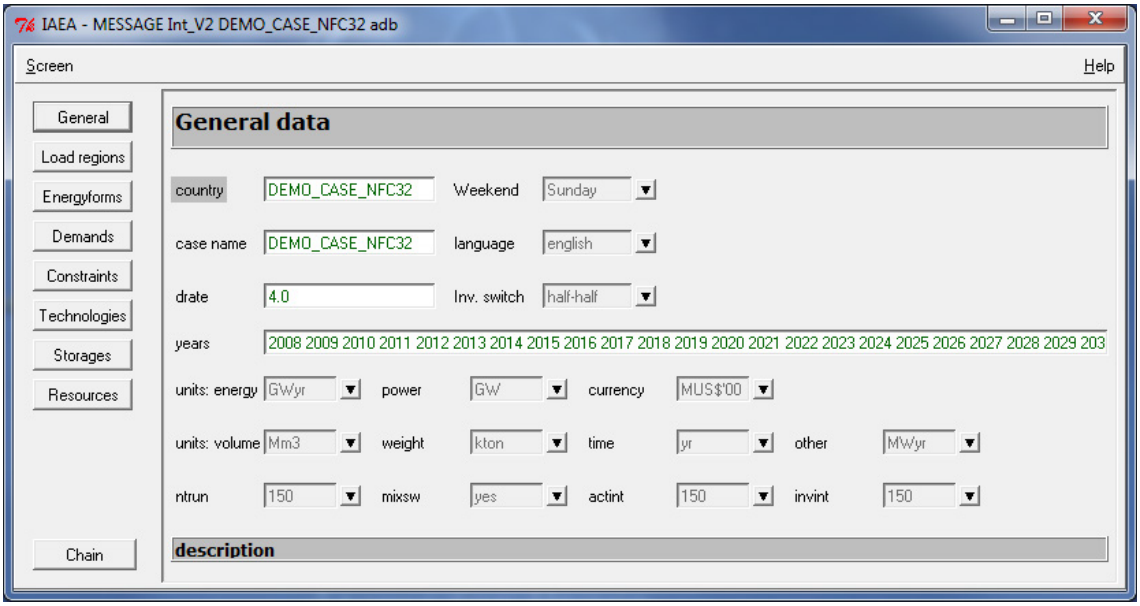
4.2.1. MESSAGE modelling of a closed fuel cycle with plutonium multi-recycling (Demo_Case_NFC32)

The MESSAGE energy chain of the NES is shown in Fig. 4.18. Input data for LWR, ALWR and HWR technologies can be taken from Demo_Case_NFC1. This example uses basic units of GW·a for energy, GW for power and tonne for weight. Basic units are entered in general data form (see Fig. 4.19).



Level	Energyform	Producers	Consumers
Resources	Unat		cnLWR cnHWR
Front_end	cnLWR	cnLWR	enLWR
	cnHWR	cnHWR	fuHWR
	enLWR	enLWR	fuUOXLWR
	enALWR	enLWR	fuUOXLWR
	fuUOXLWR	fuUOXLWR	LWRUOX
	SWLWR	SWLWR	enLWR
	SWALWR	SWALWR	enLWR
	fuAUOXLWR	fuUOXLWR	ALWRUOX
	fuHWR	fuHWR	HWR
	fuFR	fuFR	FR
	fuAXBLFR	fuAXBLFR	FR
	fuRADBLFR	fuRADBLFR	FR
Back_end	dummy	fcLWR fcALWR fcHWR fcFR	
	RepSF	ReLWR ReFR	
	SFLWR	fsLWR	ReLWR
	SFALWR	fsALWR	ReLWR
	SFHWR		
	SFFR	fsFR	ReFR
	crLWR		fcLWR
	crALWR		fcALWR
	crHWR		fcHWR
	crFR		fcFR
Secondary	Electricity	LWRUOX	

FIG. 4.18. *Energy and technology chain of a global NES.*



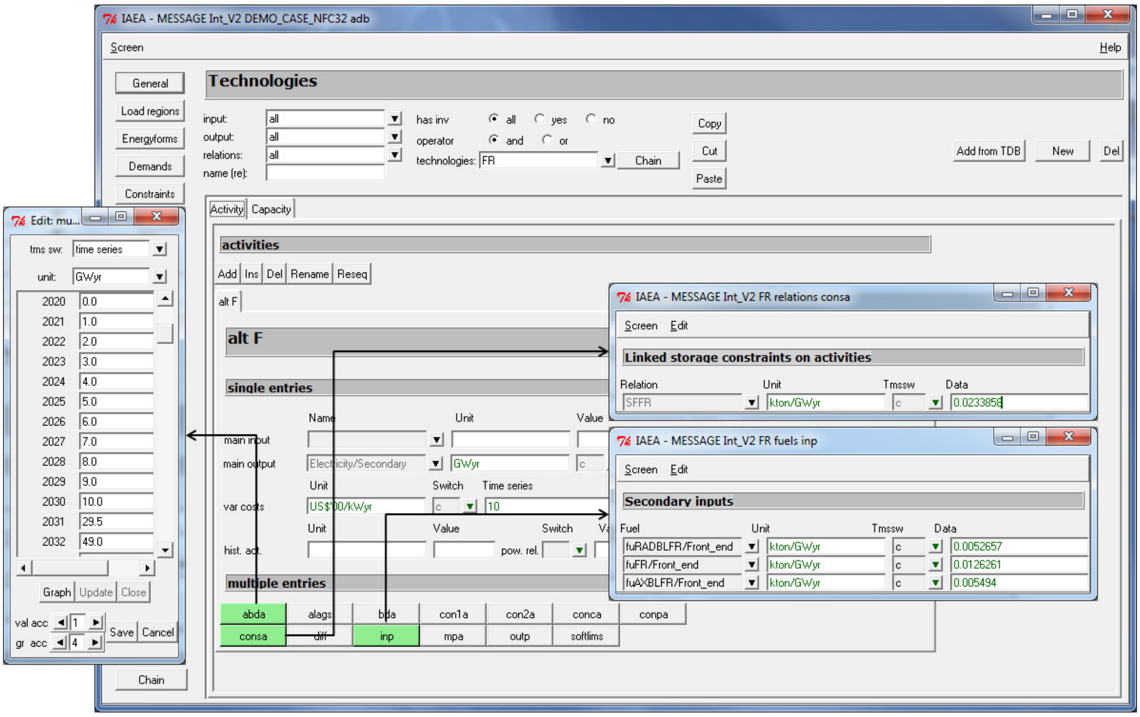
General data

country: DEMO_CASE_NFC32
Weekend: Sunday
case name: DEMO_CASE_NFC32
language: english
drate: 4.0
Inv. switch: half-half
years: 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 203
units: energy: GWyr
power: GW
currency: MUS$'00
units: volume: Mm3
weight: kton
time: yr
other: MWyr
ntrun: 150
mixsw: yes
actint: 150
invint: 150

description

FIG. 4.19. *Defining unit type in the general data screen.*

Constraints on the introduction of a fast reactor in the period 2020–2050 are entered with the tab labelled *adba* on the fast reactor technologies window (see Fig. 4.20).



IAEA - MESSAGE Int_V2 DEMO_CASE_NFC32 adb

Technologies

input: all
output: all
relations: all
name (re):
has inv: ● all ○ yes ○ no
operator: ● and ○ or
technologies: FR

activities

alt F

single entries

	Name	Unit	Value
main input			
main output	Electricity/Secondary	GWyr	c

	Unit	Switch	Time series
var costs	US$'00/kWyr	c	10

multiple entries

Edit: mu...

tms sw: time series
unit: GWyr

2020	0.0
2021	1.0
2022	2.0
2023	3.0
2024	4.0
2025	5.0
2026	6.0
2027	7.0
2028	8.0
2029	9.0
2030	10.0
2031	29.5
2032	49.0

val acc: 1
gr acc: 4

IAEA - MESSAGE Int_V2 FR relations consa

Linked storage constraints on activities

Relation	Unit	Tmssw	Data
SFFR	kton/GWyr	c	0.0233858

IAEA - MESSAGE Int_V2 FR fuels inp

Secondary inputs

Fuel	Unit	Tmssw	Data
fuRADBLFR/Front_end	kton/GWyr	c	0.0052657
fuFR/Front_end	kton/GWyr	c	0.0126261
fuAXBLFR/Front_end	kton/GWyr	c	0.005494

FIG. 4.20. Fast reactor technology in the activity window.

The following results are extracted and analysed:

- — Nuclear electricity generation structure;
- — Natural uranium consumption;
- — Fresh fuel requirements;
- — Enrichment requirements;
- — Reprocessing requirements;
- — Spent fuel accumulation.

The structure of nuclear electricity generation is displayed in Fig. 4.21. In this scenario, the demand for HWRs is set at 6% of the total demand of thermal power reactors. FR_MOX will be commissioned in 2020 at a fixed rate of energy generation per year until 2050. After 2050, fast reactors will be introduced further according to plutonium availability and economic expediency.

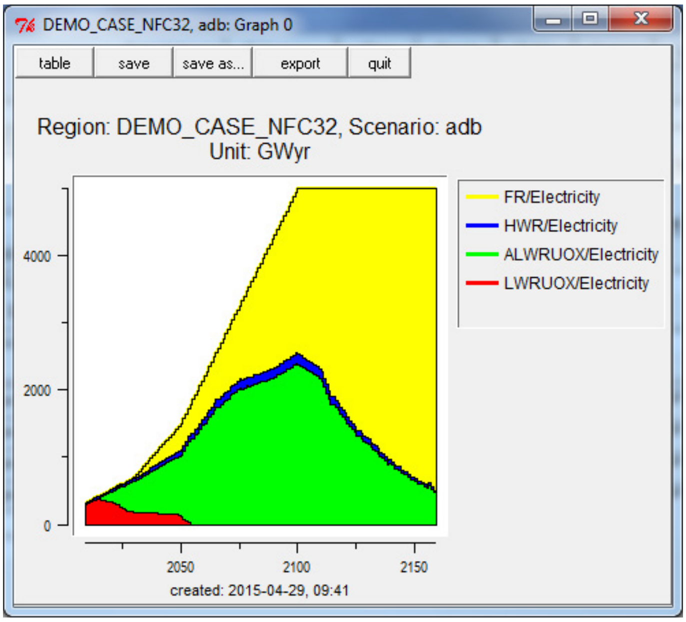


FIG. 4.21. *Nuclear electricity generation structure.*

The consumption of natural uranium over a 100 year period is about 25 million tonnes (see Fig. 4.22). For comparison cumulative uranium consumption is 38 million tonnes for a once through global nuclear fuel cycle in Demo_Case_NFC1. Uranium recovered from phosphates will be used as of 2080, about ten years earlier than in the case of the once through fuel cycle.

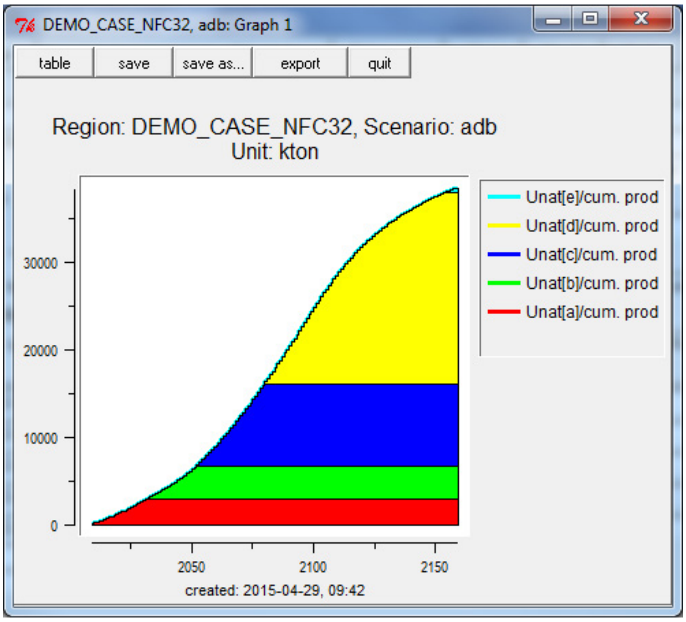


FIG. 4.22. *Natural uranium consumption.*

The requirements of front end fuel cycle facilities, such as UOX and MOX fuel fabrication and enrichment, are shown in Figs 4.23 and 4.24. By the end of the century, requirements for fresh fuel fabrication will account to about 45 kt/a, 30 kt/a and 55 kt/a for an LWR, an HWR and a fast reactor, respectively. Enrichment requirements will be about 400 kt SWU/a.

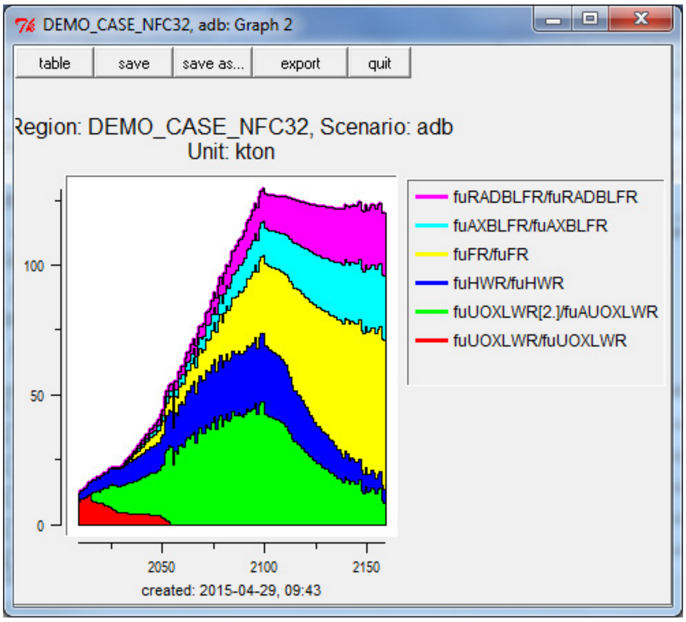


FIG. 4.23. Fuel fabrication requirements.

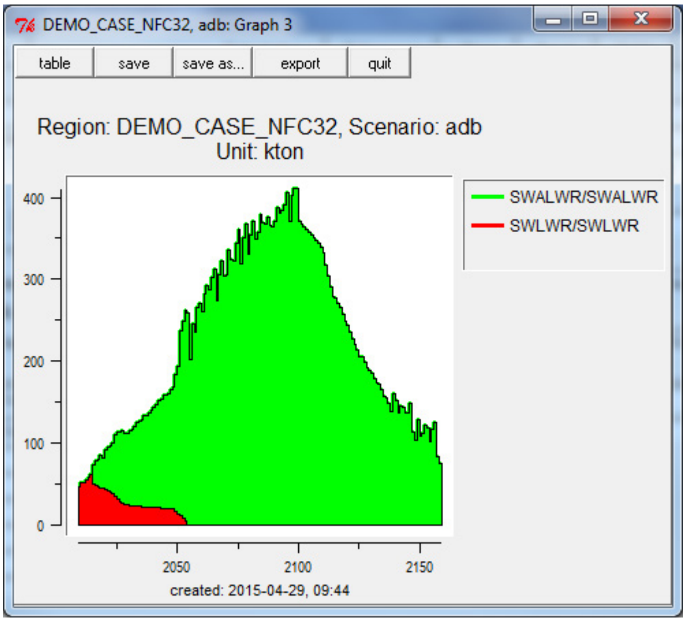


FIG. 4.24. Enrichment requirements.

Spent fuel for reprocessing can be extracted from reprocessing technology. The model assumes that 40 kt/a of UOX fuel and 55 kt/a of MOX+blanket fuel will be reprocessed by the end of the century (see Fig. 4.25). Accumulations of spent fuel in storage are given in Fig. 4.26.

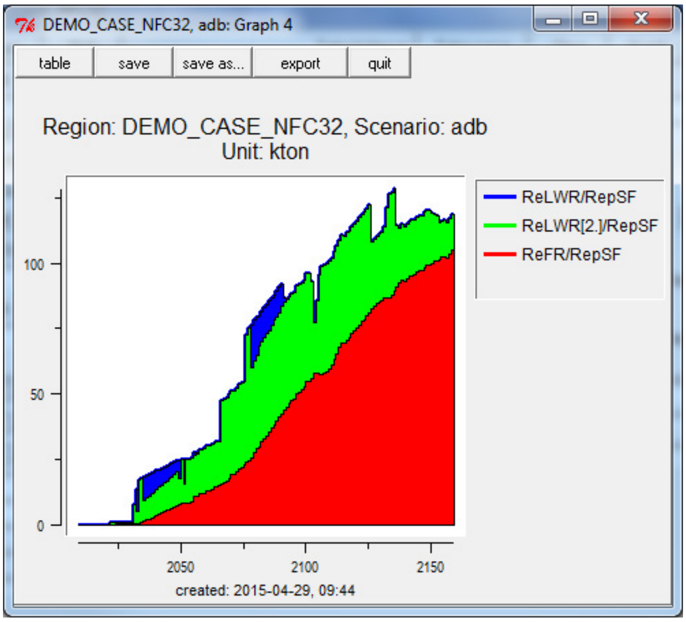


FIG. 4.25. *Reprocessing requirement.*

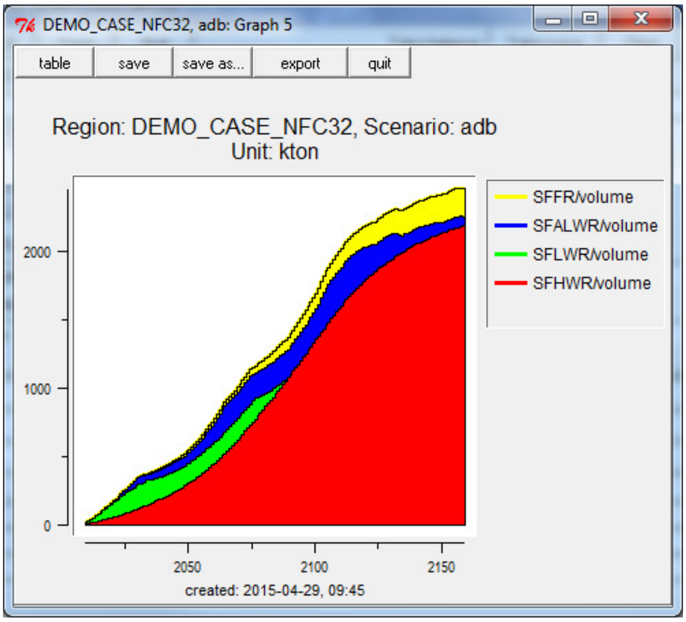


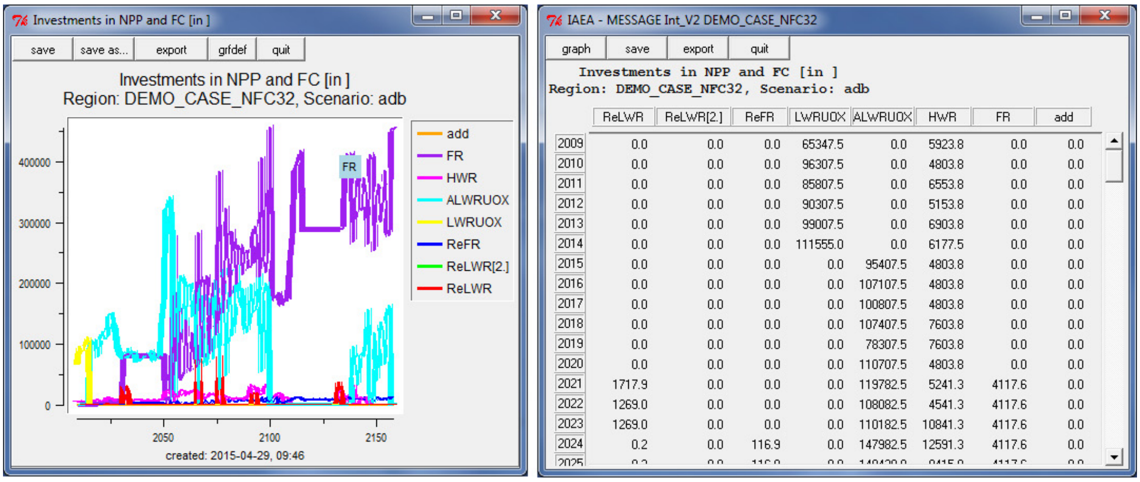
FIG. 4.26. *Spent fuel accumulation in storages.*

4.2.2. Economic results of MESSAGE modelling for a closed fuel cycle with plutonium multi-recycling

In terms of economic results, three tables were prepared to calculate the following results:

- Annual investments in the NPP and fuel cycle;
- Annual expenditure on the fuel cycle and O&M of the NPP;
- LUAC&LUOM.

Annual investments in the NPP and the fuel cycle are given in Fig. 4.27, as prepared with the tab labelled *Predef. Tables*. Investments and other costs are measured in millions of US dollars, since capacity has the unit GW and overnight cost has the unit US $/kW (GW × US $/kW = US $1 million). Annual investments in an HWR, an LWR, an ALWR, a fast reactor and reprocessing facilities are given in the graph and table.

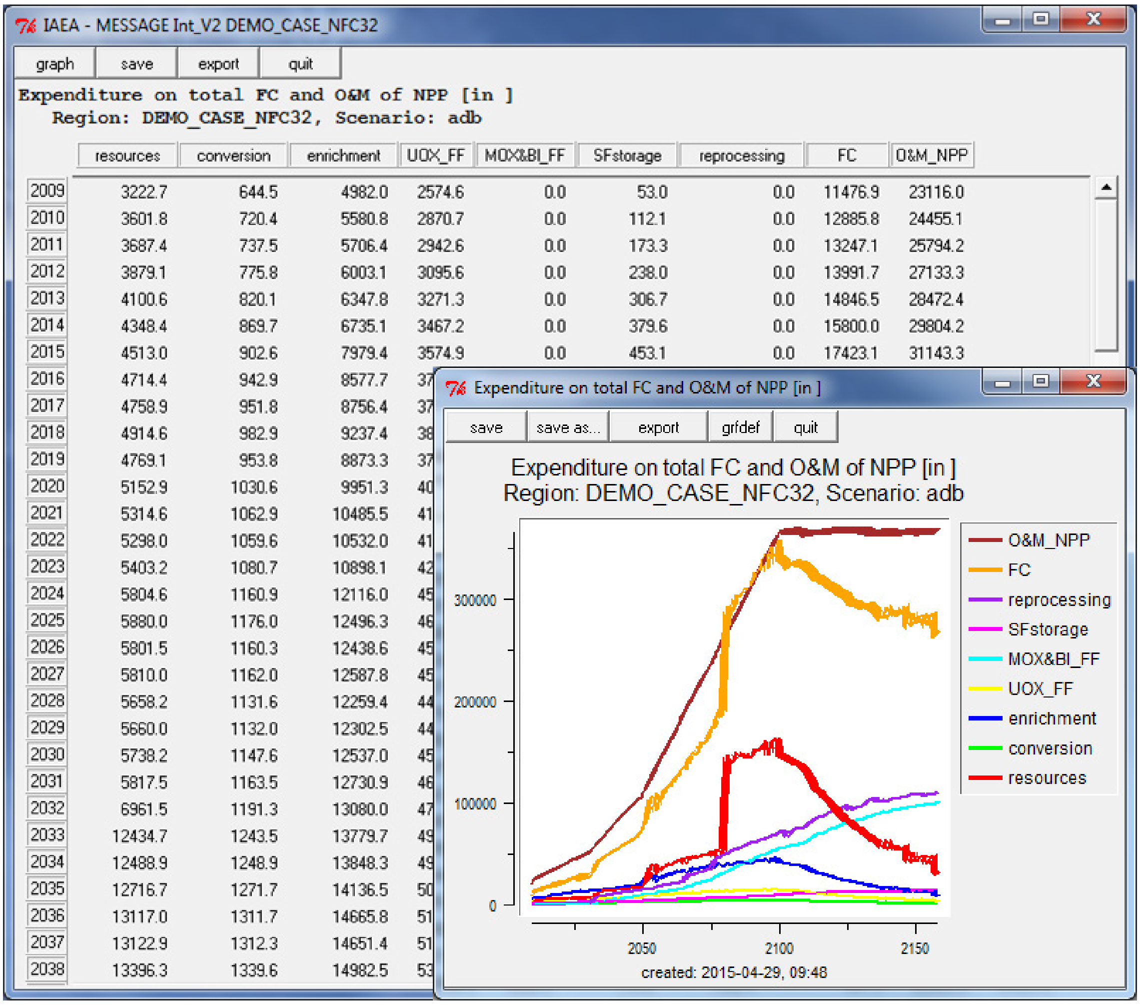


Investments in NPP and FC [in]
Region: DEMO_CASE_NFC32, Scenario: adb

	ReLWR	ReLWR[2.]	ReFR	LWRUOX	ALWRUOX	HWR	FR	add
2009	0.0	0.0	0.0	65347.5	0.0	5923.8	0.0	0.0
2010	0.0	0.0	0.0	96307.5	0.0	4803.8	0.0	0.0
2011	0.0	0.0	0.0	85807.5	0.0	6553.8	0.0	0.0
2012	0.0	0.0	0.0	90307.5	0.0	5153.8	0.0	0.0
2013	0.0	0.0	0.0	99007.5	0.0	6903.8	0.0	0.0
2014	0.0	0.0	0.0	111555.0	0.0	6177.5	0.0	0.0
2015	0.0	0.0	0.0	0.0	95407.5	4803.8	0.0	0.0
2016	0.0	0.0	0.0	0.0	107107.5	4803.8	0.0	0.0
2017	0.0	0.0	0.0	0.0	100807.5	4803.8	0.0	0.0
2018	0.0	0.0	0.0	0.0	107407.5	7603.8	0.0	0.0
2019	0.0	0.0	0.0	0.0	78307.5	7603.8	0.0	0.0
2020	0.0	0.0	0.0	0.0	110707.5	4803.8	0.0	0.0
2021	1717.9	0.0	0.0	0.0	119782.5	5241.3	4117.6	0.0
2022	1269.0	0.0	0.0	0.0	108082.5	4541.3	4117.6	0.0
2023	1269.0	0.0	0.0	0.0	110182.5	10841.3	4117.6	0.0
2024	0.2	0.0	116.9	0.0	147982.5	12591.3	4117.6	0.0

FIG. 4.27. *Annual investments in the NPP.*

Annual running expenditure on the fuel cycle and O&M of the NPP are given in Fig. 4.28. Expenditure on the fuel cycle includes resources, conversion, enrichment, UOX and MOX+blanket fresh fuel fabrication, reprocessing and spent fuel storage costs. Annual expenditure on O&M of the NPP (fixed and variable O&M) was also calculated. Costs and investment are measured in millions of US dollars.



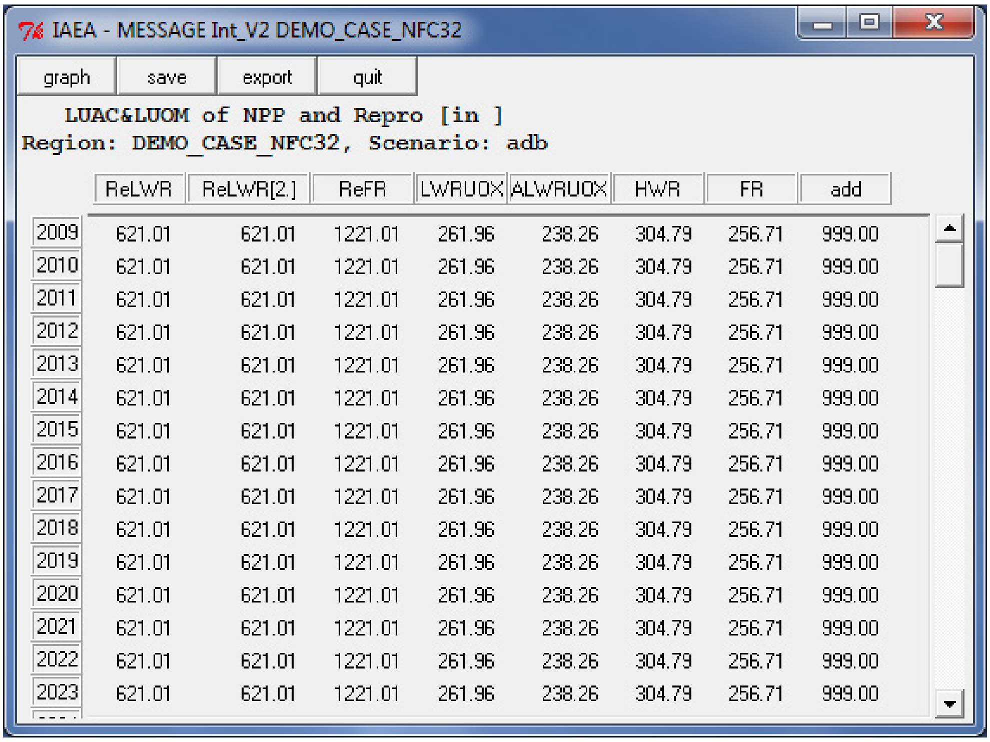
Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC32, Scenario: adb

	resources	conversion	enrichment	UOX_FF	MOX&BI_FF	SFstorage	reprocessing	FC	O&M_NPP
2009	3222.7	644.5	4982.0	2574.6	0.0	53.0	0.0	11476.9	23116.0
2010	3601.8	720.4	5580.8	2870.7	0.0	112.1	0.0	12885.8	24455.1
2011	3687.4	737.5	5706.4	2942.6	0.0	173.3	0.0	13247.1	25794.2
2012	3879.1	775.8	6003.1	3095.6	0.0	238.0	0.0	13991.7	27133.3
2013	4100.6	820.1	6347.8	3271.3	0.0	306.7	0.0	14846.5	28472.4
2014	4348.4	869.7	6735.1	3467.2	0.0	379.6	0.0	15800.0	29804.2
2015	4513.0	902.6	7979.4	3574.9	0.0	453.1	0.0	17423.1	31143.3
2016	4714.4	942.9	8577.7	37					
2017	4758.9	951.8	8756.4	37					
2018	4914.6	982.9	9237.4	38					
2019	4769.1	953.8	8873.3	37					
2020	5152.9	1030.6	9951.3	40					
2021	5314.6	1062.9	10485.5	41					
2022	5298.0	1059.6	10532.0	41					
2023	5403.2	1080.7	10898.1	42					
2024	5804.6	1160.9	12116.0	45					
2025	5880.0	1176.0	12496.3	46					
2026	5801.5	1160.3	12438.6	45					
2027	5810.0	1162.0	12587.8	45					
2028	5658.2	1131.6	12259.4	44					
2029	5660.0	1132.0	12302.5	44					
2030	5738.2	1147.6	12537.0	45					
2031	5817.5	1163.5	12730.9	46					
2032	6961.5	1191.3	13080.0	47					
2033	12434.7	1243.5	13779.7	49					
2034	12488.9	1248.9	13848.3	49					
2035	12716.7	1271.7	14136.5	50					
2036	13117.0	1311.7	14665.8	51					
2037	13122.9	1312.3	14651.4	51					
2038	13396.3	1339.6	14982.5	53					

Expenditure on total FC and O&M of NPP [in]
Region: DEMO_CASE_NFC32, Scenario: adb

FIG. 4.28. Annual expenditure on the fuel cycle and O&M of the NPP.

LUAC&LUOM for the NPP was prepared with the help of the tab labelled *Predef. Tables*. The results in US $/kW·a are 261.96, 238.26, 304.79, 256.71 for an LWR, an ALWR, an HWR and a fast reactor, respectively (see Fig. 4.29). LUAC&LUOM for reprocessing facilities is US $621/kg for LWR spent fuel and US $1221/kg for fast reactor spent fuel.



LUAC&LUOM of NPP and Repro [in]
Region: DEMO_CASE_NFC32, Scenario: adb

	ReLWR	ReLWR[2.]	ReFR	LWRUOX	ALWRUOX	HWR	FR	add
2009	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2010	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2011	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2012	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2013	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2014	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2015	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2016	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2017	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2018	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2019	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2020	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2021	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2022	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00
2023	621.01	621.01	1221.01	261.96	238.26	304.79	256.71	999.00

FIG. 4.29. LUAC&LUOM for the NPP.

Annex I

MESSAGE DATA ON DEMO_CASE_NFC12

Annex I provides input data on demonstration case Demo_Case_NFC12 for a heavy water reactor (HWR), a light water reactor (LWR) and an advanced light water reactor (ALWR) given in Tables I–1 and I–2 and the associated fuel cycles given in Tables I–3 and I–4 in MESSAGE format. The data units are also given as they are identified in MESSAGE.

TABLE I–1. REACTOR TECHNOLOGY ACTIVITIES

	HWR	LWR	ALWR
Main input	None	None	None
Main output (GW·a)	1	1	1
Secondary input (kt/GW·a)	0.173 809 544	0.024 579 125	0.017 885
Secondary output (kt/GW·a)	0.173 809 544	0.024 579 125	0.017 885
Relation 1	−0.94	0.06	0.06
Variable cost (US $/kW·a)	15	10	10

TABLE I–2. REACTOR TECHNOLOGY CAPACITIES

	HWR	LWR	ALWR
Plant factor	0.8	0.8	0.8
Plant life (a)	40	40	60
Investment cost (US $/kW)	3 500	3 000	3 000
Fixed cost (US $/kW/a)	55	50	50
Corin/corout (kt/GW)	0	0.058 99	0.071 932
Construction time (a)	5	5	5

TABLE I–3. FUEL CYCLE TECHNOLOGY ACTIVITIES

	Main input (kt)	Main output (kt)	Secondary input (kt/kt)	Consa (kt/kt)	Variable costs (US $/kg)
cnLWR	1	1	None	None	8
cnHWR	1	1	None	None	8
enLWR	None	1	9.295 499	8.295 499	None
alt a	None	None	8.734 289	None	None
alt b	None	None	9.295 499 8.734 289	9.295 499	None
SWLWR	None	1	None	None	110
SWALWR	None	1	None	None	110
fuUOXLWR	1	1	None	None	275
fuHWR	1	1	None	None	65
fcLWR	1	1	None	1	None
fcALWR	1	1	None	1	None
fcHWR	1	1	None	1	None

TABLE I–4. STORAGES

	Retention time (year)	Max. volume (US $/kg)	Cost (US $/kg)
DepU	None	99 999	None
SFLWR	5	99 999	5
SFALWR	5	99 999	5
SFHWR	5	99 999	5

Annex II

MESSAGE DATA ON DEMO_CASE_NFC23

Annex II provides input data on demonstration case Demo_Case_NFC23 for a heavy water reactor (HWR), a light water reactor (LWR) using UOX fuel and an LWR_MOX using MOX and UOX fuels) given in Tables II–1 and II–2 and the associated fuel cycles given in Tables II–3 to II–5 in MESSAGE format. The data units are also given as they are identified in MESSAGE format.

TABLE II–1. REACTOR TECHNOLOGY ACTIVITIES

	HWR	LWR	LWR_MOX
Main input	None	None	None
Main output (GW·a)	1	1	1
Secondary input (kt/GW·a)	0.173 809 544	0.024 579 125	0.016 386 0.008 193
Secondary output (kt/GW·a)	0.173 809 544	0.024 579 125	None
Consa (kt/GW·a)	None	None	0.016 386 0.008 193
Relation 1	−0.94	0.06	0.06
Variable costs (US $/kW·a)	15	10	10

TABLE II–2. REACTOR TECHNOLOGY CAPACITIES

	HWR	LWR	LWR_MOX
Plant factor	0.8	0.8	0.8
Plant life (a)	40	40	40
Investment cost (US $/kW)	3 500	3 000	3 000
Fixed cost (US $/kW/a)	55	50	50
Corin/corout (kt/GW)	0	0.058 99	0.039 327 0.019 663
Construction time (a)	5	5	5

TABLE II–3. FUEL CYCLE TECHNOLOGY ACTIVITIES

	Main input (kt)	Main output (kt)	Secondary input (kt/kt)	Consa (kt/kt)	Variable costs (US $/kg)
cnLWR	1	1	None	None	8
cnHWR	1	1	None	None	8
enLWR	None	1	9.295 499 8.734 289	8.295 499	None
SWLWR	None	1	None	None	110
fuMOXLWR	None		None	None	None
fuUOXLWR	1	1	None	None	275
fuHWR	1	1	None	None	65
fcLWR	1	1	None	1	None
fcMOXLWR	1	1	None	1	None
fcHWR	1	1	None	1	None
fsLWR	1	1	None	−1	None
ReLWR	1	1	None	0.001 457 28 (Mac) 0.942 187 3 (ReUL) 0.009 953 (Putot) 0.046 4 (FRr)	400

TABLE II–4. FUEL CYCLE TECHNOLOGY CAPACITIES

Capacity window	ReLWR
Plant factor	1
Plant life (a)	60
Investment cost (US $/kg)	5000
Construction time (a)	5

TABLE II–5. STORAGES

	Retention time (a)	Max. volume (kt)	Cost (US $/kg)
DepU	None	99 999	None
SFLWR	5	99 999	5
SFMOXLWR	5	99 999	5
SFHWR	5	99 999	5
Putot	None	99 999	None
ReUL	None	99 999	None
MAc	None	99 999	None
FPr	None	99 999	None

Annex III

MESSAGE DATA ON DEMO_CASE_NFC32

Annex III provides input data on demonstration case Demo_Case_NFC32 for a heavy water reactor (HWR), a light water reactor (LWR), an advanced light water reactor (ALWR) and a fast reactor (FR) given in Tables III–1 and III–2 and the associated fuel cycles given in Tables III–3 to III–5 in MESSAGE format. The data units are also given as they are identified in MESSAGE format.

TABLE III–1. REACTOR TECHNOLOGY ACTIVITIES

	HWR	LWR	ALWR	FR
Main input	None	None	None	None
Main output (GW·a)	1	1	1	1
Secondary input (kt/GW·a)	0.173 809 544	0.024 579 125	0.017 885	0.005 265 7 0.012 626 1 0.005 494
Secondary output (kt/GW·a)	0.173 809 544	0.024 579 125	0.017 885	None
Consa	None	None	None	0.023 385 8
Relation 1	−0.94	0.06	0.06	None
Variable costs (US $/kW·a)	15	10	10	10

TABLE III–2. REACTOR TECHNOLOGY CAPACITIES

	HWR	LWR	ALWR	FR
Plant factor	0.8	0.8	0.8	0.85
Plant life (a)	40	40	60	60
Investment cost (US $/kW)	3 500	3 000	3 000	3 500
Fixed cost (US $/kW/a)	55	50	50	55
Corin (kt/GW)	0	0.058 99	0.071 932	0.002 593 16 0.003 796 5 0.001 652
Corout (kt/GW)	0	0.058 99	0.071 932	0.008 04
Construction time (a)	5	5	5	5

TABLE III–3. FUEL CYCLE TECHNOLOGY CAPACITIES

Capacity window	ReLWR	ReFR
Plant factor	1	1
Plant life (a)	60	60
Investment cost (US $/kg)	5000	5000
Construction time (a)	5	5

TABLE III–4. FUEL CYCLE TECHNOLOGY ACTIVITIES

	Main input (kt)	Main output (kt)	Secondary input (kt/kt)	Consa (kt/kt)	Variable costs (US $/kg)
cnLWR	1	1	None	None	8
cnHWR	1	1	None	None	8
enLWR	None	1	9.295 499	8.295 499	None
alt a	None	None	8.734 289	None	None
alt b	None	None	9.295 499 8.734 289	9.295 499	None
SWLWR	None	1	None	None	110
SWALWR	None	1	None	None	110
fuUOXLWR	1	1	None	None	275
fuHWR	1	1	None	None	65
fuFR	None		None	−0.781 5 −0.218 5	None
fuAXBLFR	None	1	None	−1	None
fuRADBLFR	None	1	None	−1	None
fcLWR	1	1	None	1	None
fcALWR	1	1	None	1	None
fcHWR	1	1	None	1	None
fcFR	1	1	None	None	None
fsLWR	1	1	None	−1	None
fsALWR	1	1	None	−1	None
fsFR	1	1	None	−1	None

TABLE III–4. FUEL CYCLE TECHNOLOGY ACTIVITIES (cont.)

	Main input (kt)	Main output (kt)	Secondary input (kt/kt)	Consa (kt/kt)	Variable costs (US $/kg)
ReLWR	1	1	None	0.001 457 28 (Mac) 0.942 187 3 (ReUL) 0.009 953 (Putot) 0.046 4 (FRr)	400
ReFR	1	1	None	0.002 339 938 (Mac) 0.840 400 27 (RedepU) 0.117 852 997 (Putot) 0.038 409 189 (FRr) 0.000 897 607 (Puloss)	1 000

TABLE III–5. STORAGES

	Retention time (a)	Max. volume (kt)	Cost (US $/kg)
DepU	None	99 999	None
SFLWR	5	99 999	5
SFALWR	5	99 999	5
SFHWR	5	99 999	5
SFFR	2	99 999	5
Putot	None	99 999	None
ReUL	None	99 999	None
MAc	None	99 999	None
FPr	None	99 999	None
RedepU	None	99 999	None
Puloss	None	99 999	None

ABBREVIATIONS

a	year
alt	alternative
ALWR	advanced light water reactor
Coal-Extr	coal extraction
Coal PP	coal power plant
DepU	depleted uranium
EFPD	effective full power days
Elec_TD	electricity transmission and distribution
FP	fission products
FR	fast reactor
GAINS	Global Architecture of Innovative Nuclear Energy Systems Based on Thermal and Fast Reactors Including a Closed Fuel Cycle
GW·d	gigawatt-days
GW(e)	gigawatt (electrical)
HM	heavy metal
HWR	heavy water reactor
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
kg HM	kilogram of heavy metal
kg SF	kilogram of spent fuel
kg SWU	kilogram of separative work unit
kg U	kilogram of uranium
kW(e)	kilowatt (electrical)
LUAC	levelized unit lifecycle amortization cost
LUEC	levelized unit energy cost
LUFC	levelized unit lifecycle fuel cost
LUOM	levelized unit lifecycle operation and maintenance cost
LWR	light water reactor
MA	minor actinide
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impacts
MOX	mixed oxide
Nat U	natural uranium
NES	nuclear energy system
NFC	nuclear fuel cycle
NPP	nuclear power plant
O&M	operation and maintenance
Oil_Imp	oil importation
Oil_PP	oil power plant
Oil_P_S	oil processing and supply
Oil_S_F	oil secondary to final
S	storage
SF	spent fuel
SWU	separative work unit
t FP	tonne of fission products
t HM	tonne of heavy metal
t SWU	tonne of separative work unit
UOX	uranium oxide

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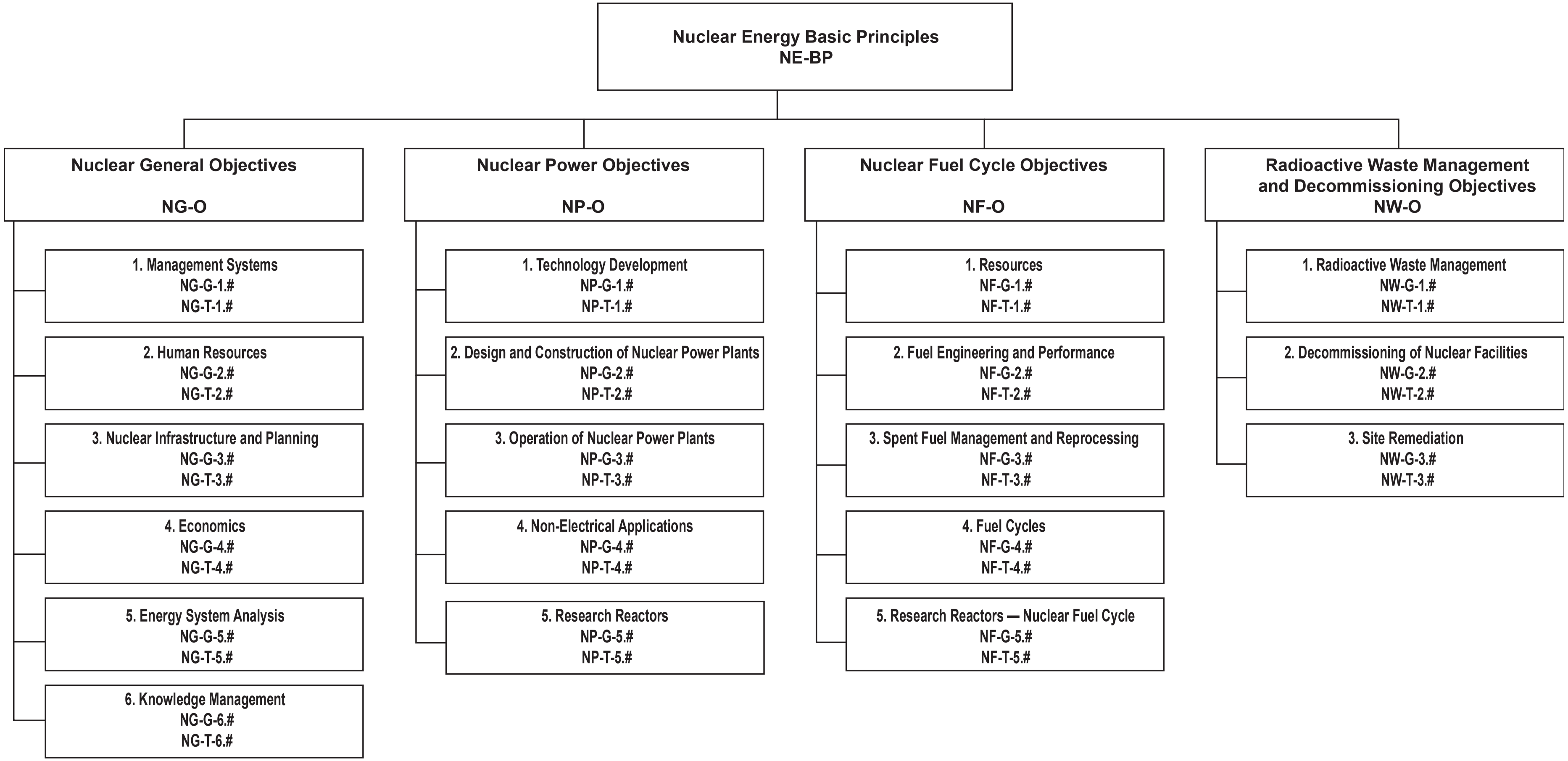

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