Abstract

SCHWEITZER, TYLER M. Improved Building Methodology and Analysis of Delay Scenarios of Advanced Nuclear Fuel Cycles with the **V**erif**i**able Fuel Cycle **Si**mulati**on** Model (VISION). (Under the Direction of Paul J. Turinsky.)

The goal of this research is to help better understand the areas of uncertainty with advanced nuclear fuel cycles. The Department of Energy has started several large scale programs that will explore and develop advanced nuclear fuel cycle components. One of the key components to this endeavor is a system dynamics model that simulates the construction of nuclear reactors and their required support facilities in a growing energy demand environment. This research developed methods to more accurately determine when to build facilities based upon forecasting methods and inventories. The next phase of the research was to analyze lead times on constructing light water reactor spent fuel separation facilities and possible associated upset events and their mitigation strategies.

The results show a smooth building rate for fast burner reactors, which ensures that the reactors will not run out of fuel supply for their entire lifetime. After analyzing several separation facility sizes and variable construction lead times, it was determined that there is an optimal separation facility size and an optimal lead time for a given growth rate for fast reactors. This optimal case kept the separated material inventory at a minimum value, while also building inventories for reactors that are getting ready to begin operation. Upset events were analyzed in order to determine how the system will respond to a separation facility not starting up on time and a separation facility being taken offline. The results show that increasing the lead time on separation facilities is the best way to mitigate a delayed separation facility and decreasing the separation facility size would better mitigate a facility being taken offline. The use of a separated materials

fuel bank was also critical in ensuring that no reactors were starved of fuel during these upset events. In conclusion the work done in this thesis helped to create a better understanding for how different facilities interact in an advanced nuclear fuel cycle.

Improved Building Methodology and Analysis of Delay Scenarios of Advanced Nuclear Fuel Cycles with the **V**erif**i**able Fuel Cycle **Si**mulati**on** Model (VISION)

by
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Biography

Tyler Schweitzer was born on May 31, 1984 in Fayetteville, AR and grew up in Charlotte, NC. After graduating from David W. Butler High School in June of 2002, Tyler enrolled at NC State to pursue a degree in Nuclear Engineering. During his time as an undergraduate at NC State Tyler served for 3 years on the Engineers' Council, where the last two years he served as Chair of the Council. Tyler led the Council in creating a $100,000 scholarship endowment fund, which is the largest gift by any single student organization. In May of 2006 Tyler graduated with a BS in Nuclear Engineering and received an award for scholarly achievement in Nuclear Engineering.

Upon completion of his undergraduate degree, Tyler continued at NC State in pursuit of a Master's of Science in Nuclear Engineering. As a graduate student, Tyler served 2 years in the Student Senate representing the Graduate School and 2 years on the Nuclear Engineering Student Delegation to Washington, D.C. Tyler has had industry experience through 3 different summer internship at Knolls Atomic Power Laboratory, General Electric – Hitachi Nuclear and Idaho National Laboratory. Once Tyler has completed all degree requirements, he will start his career as an engineer for General Electric – Hitachi Nuclear in Wilmington, NC.

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Nomenclature

LWR – Light Water Reactor
LWRmf – Light Water Reactor Mixed Fuel (MOX or IMF fuel capable)
FBR – Fast Burner/Breeder Reactor
MOX – Mixed Oxide Fuel
IMF – Inert Matrix Fuel
TRU – Transuranics (Isotopes NP237 - Cf 252)
GNEP – Global Nuclear Energy Partnership
AFCI – Advanced Fuel Cycle Initiative
VISION – **V**erif**i**able Fuel Cycle **Si**mulati**on** Model
DYMOND – **Dy**namic **Mo**del of **N**uclear **D**evelopment
INL – Idaho National Laboratory
ANL – Argonne National Laboratory
SNL – Sandia National Laboratory

1 Introduction

1.1 Importance to Nuclear Industry

Over the past couple of years the US Department of Energy and President George W. Bush have announced the creation of two major programs that will study and implement a closed nuclear fuel cycle; Advanced Fuel Cycles Initiative (AFCI) and the Global Nuclear Energy Partnership (GNEP). These two initiatives were started as a result of world wide rising energy demand and an increase in the desire to use nuclear power to meet this energy demand. The AFCI will seek to explore alternative means of recycling used nuclear fuel in order to minimize the amount of nuclear waste, improve fuel cycle proliferation resistance, improve fuel cycle management through economic and safety performances, and ensure a steady supply of nuclear fuel for centuries to come (1). In order to meet these objectives the AFCI was organized into four working groups; Systems Analysis, Fuels, Separations and Transmutations. The first working group, Systems Analysis, was tasked with developing a dynamic model of the nuclear fuel cycle. As a result the **V**erif**i**able Fuel Cycle **Si**mulati**on** Model (VISION) was developed at the Idaho National Laboratory (INL) in collaboration with Sandia National Laboratory (SNL) and Argonne National Laboratory (ANL) (1).

VISION is a system dynamics model of the nuclear fuel cycle that models the US advanced commercial nuclear energy market. VISION was originally derived from the fuel cycle code DYMOND, which was developed at ANL (2). The VISION model takes the projected US energy growth rate and nuclear power market share over the next century and builds reactors in order to meet this demand, along with the necessary support facilities. Options are included in the model that will allow the user to recycle used nuclear fuel with many different separation technologies, use several different reactor and fuel types, and have several different waste management options. The results of the model will help policy makers and industry leaders know and understand the infrastructure requirements and material flows for any combination of advanced fuel cycle scenarios (1).

In order to fully understand infrastructure requirements, plausible upset scenarios need to be analyzed, which will disrupt the normal flow of material and building and operation of facilities. These upset scenarios will show the major bottlenecks in the process of any advanced fuel cycle scenario. During upset events, a predefined series of mitigation strategies will be enacted to help mitigate the negative effects of the event. Testing a combination of upset events and mitigation strategies, the model can be used to identify the appropriate deployment of facilities to build a robust fuel cycle that industry representatives and policy makers can rely on to fulfill the goals of the AFCI.

1.2 Reason for Using VISION

The AFCI has designated VISION as the system dynamic and integration model in order to evaluate all of the AFCI objectives; waste management, proliferation resistance, energy recovery and systematic fuel management. VISION is being developed at the Idaho National Laboratory in conjunction with Argonne National Laboratory, Sandia National Laboratory, North Carolina State University, University of Wisconsin, Idaho State University, University of Illinois at Urbana-Champaign, The Ohio State University and the University of Texas at Austin. VISION is written with Powersim Studio, which is a commercially available system dynamics software package. This software allows for modeling of material stock and flows that are commonly found in the US nuclear fuel cycle and expected to be present in advanced nuclear fuel cycles (1) (2) (7).

There are other fuel cycle codes that were analyzed before AFCI decided that VISION needed to be developed. These codes include CAFCA, DANESS and DYMOND (2) (7). CAFCA is a multi-region fuel cycle code written in MATLAB® and is being developed at MIT. The model builds facilities based on energy demand and the objective of minimizing spent nuclear fuel. A load factor is used to control the amount of spent fuel in the system; if the load factor is not met, then a feedback loop will reset and iterate the model until the load factor is met. This iteration was one of the main reasons why AFCI decided not to use CAFCA. The second code analyzed was DANESS, which was developed at ANL using the iThink software. DANESS can analyze several different reactor and fuel types and has the capability to perform an economic analysis on the system. The final code analyzed was the DYMOND fuel cycle code. DYMOND was built for the Generation IV Fuel Cycle Cross Cut group using the iThink/Stella software (1). The limitations of the iThink/Stella software were the main factor in the AFCI's decision to switch software platforms and develop the VISION code using Powersim. All of the features found in the DYMOND code were added to the VISION code (2) (7).

1.2.1 Background on System Dynamics

A professor of System Dynamics, Robert Geoffrey Coyle, once defined system dynamics as:

> "System Dynamics is a method of analyzing problems in which time is an important factor, and which involve the study of how a system can be defended against, or made to benefit from, the shocks which fall upon it from the outside world" (4).

The AFCI is striving to solve the problem of meeting the growing energy demand through nuclear power and minimizing its effect on the environment through its main objectives. System dynamics will help scientists and engineers to understand how system factors can either hinder or help the advancement of these technologies.

The use of system dynamics for an advanced fuel cycle model is applicable because system dynamics was built based on the concept of feedback control theory. This concept of feedback control allows for control variables to be compared to reference variables and the system will respond to correct any discrepancy in these variables. This is applicable to advanced fuel cycles because the main control variable that drives the system is energy growth and there are a series of feedback loops that help to ensure the electric production will continue to grow, while also meeting other AFCI requirements. System dynamics also allows for the modeling of material flow through a system. Since advanced fuel cycles have material flowing in many different areas, it is important that the software used to model this flow can accurately and easily track this material (1) (3) (4).

1.2.2 Background on the VISION Model

As required by the AFCI, VISION needs to be capable of bringing together many different technologies that will allow for different strategies to be analyzed. The developers of VISION created a model that would run several combinations of technology. These combinations include: once-through, limited recycle in thermal reactors, continuous recycle in thermal and/or fast reactors, sustainable recycle in fast burner reactors and/or thermal reactors (7) (8). Figure 1-1 shows a diagram of the different combinations of reactors and recycling schemes. The power plant in this figure can be any combination of fast reactor or thermal reactor. In addition to many combinations of recycling strategies there are many combinations of fuel types. Thermal reactors fuel types include MOX and IMF with variable

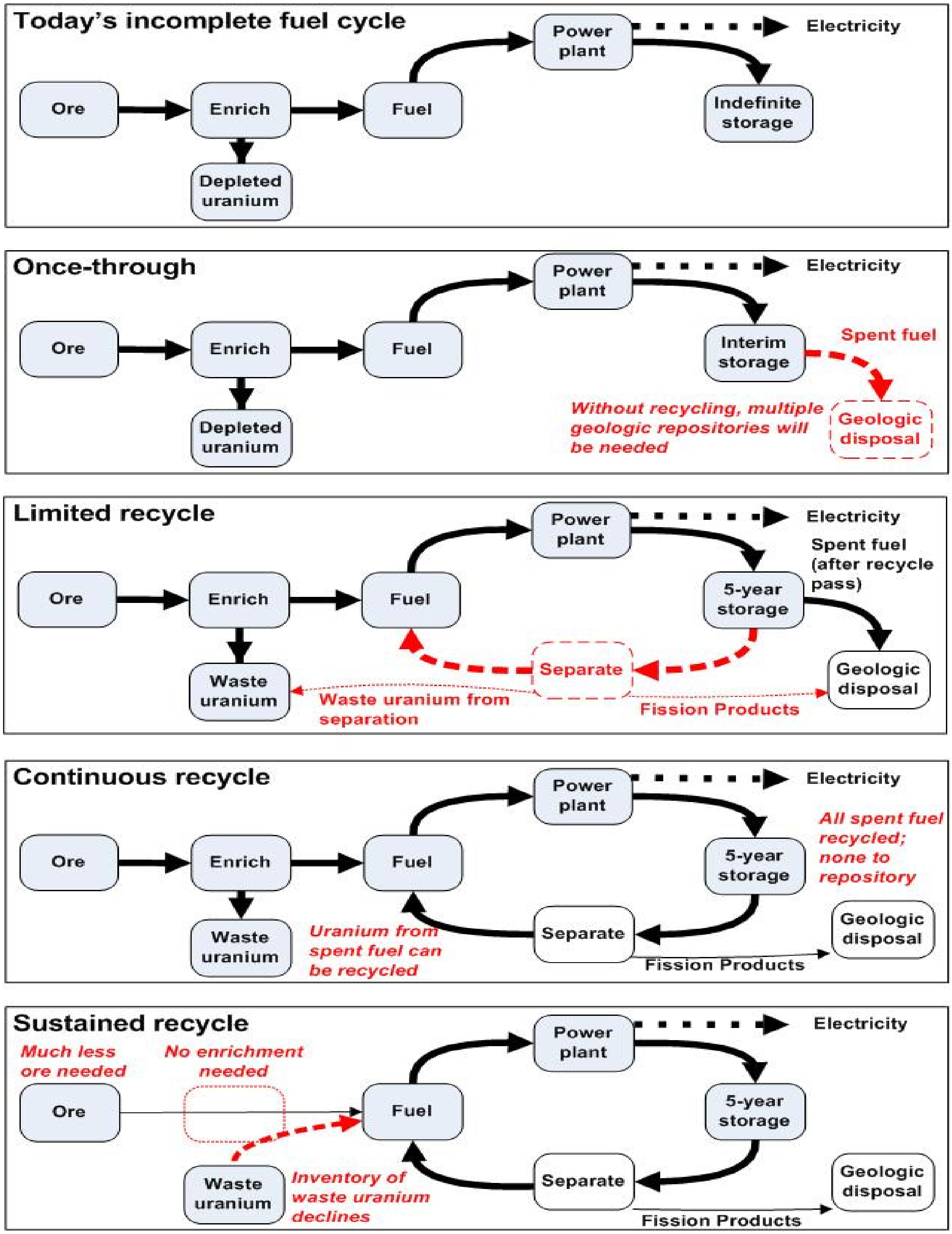

Figure 1-1: Various fuel cycles being considered by the AFCI program (7)

make-ups of transuranics. In fast burner reactors, the fuel types include options to have conversion ratios of 0, 0.25, 0.50, 0.75, 1.0 or 1.1 for a breeder reactor. Fast reactors can also choose between ceramic fuel and metal fuel. Along with the combinations of fuel types, there are several different reprocessing methods, such as UREX1-4, COEX and Electro-chemical (1) (7).

In conjunction with the system parameters, VISION also has key nuclear engineering functions that help to make the model more accurate from a neutronics and isotopic standpoint. One of the main attributes of the model is that the core neutronics calculations are not performed in the model; rather they are preformed external to the model. These external calculations have yielded composition vectors (recipes) that are imported through the model using a Microsoft Excel® interface. The recipes include isotopic weight percents for fresh fuel and spent fuel with variable burnups, conversion ratios and stages of recycling (pass 0 through 5, where pass 0 is fresh UOX fuel and pass 5 is equilibrium recycled fuel). The second important nuclear parameter that is included in VISION is the tracking and decay of 60 isotopes. These isotopes are tracked throughout wet storage, dry storage and reprocessing; while the decay is only performed during wet storage and dry storage. The main isotopes that are tracked and decayed are the transuranic isotopes, because these are the isotopes that can be used as fuel in thermal recycle or fast recycle. Other isotopes included in the tracking and decay are important fission products, such as H^3, C^{14}, Sr^{90}, Tc^{99}, I^{129} and Cs^{137}. These are used to determine repository loading calculations (1) (7).

1.3 Review of Methodology

The analysis performed in this research will be limited to one type of fuel cycle scenario: sustainable recycle in fast burner reactors (1-Tier Case). However, the logic developed for building reactors and their support facilities will apply to the other fuel cycle scenarios in the model. The overall systematic methodology that is developed in the model in this work is a revamp of the reactor order algorithm by using a look-ahead function. The look-ahead function will predict a certain number of years into the future what the electric power energy demand will be and the amount of available spent fuel ready for use in a reactor. This will then determine the mix of reactors that can be built and trigger a demand for fabricated fuel and separated material. The demand for fabricated fuel and separated material will call for an analysis of the predicted yearly capacity of fuel fabrication and separation facilities and their respective inventories. If enough capacity exists then nothing is done; however if more capacity is needed, then new facilities will be ordered at an appropriate time such that adequate supply produced by these facilities satisfies demand. The methodology developed in this work also includes mitigation scenarios for upset events, where facilities fail along the order chain or facilities are prematurely or briefly taken offline. Using this new revised methodology, VISION will more accurately reflect the true market of supply and demand in the nuclear fuel cycle.

1.4 History of Upset Scenarios

The analysis in this thesis will include two upset events 1) delaying startup of separation facilities and 2) bringing separation facilities offline after they have been operating for a certain number of years. In order to understand what real world delays could possibly look like, examples from past projects of this type were a good place to start. One facility that could be compared to the facilities within VISION is the Thermal Oxide Reprocessing Plant (Thorp) in the United Kingdom. This is a thermal recycle facility that recycles uranium and plutonium for reuse in thermal nuclear reactors. Thorp began preparation in 1974 and its builders applied for a license from the Health and Safety Executive (HSE) in 1977 and began construction in 1977. The facility was granted a "Consent to Operate" by the HSE in August of 1997, thus resulting in a 20 year construction time for a thermal separations facility (5). After being forced to completely shutdown in April of 2005 due to a leak in the separations plant, Thorp was granted a "Consent to Restart" by the HSE on January 9th, 2007 (9). This facility provides a real-world example for delaying the construction of facilities being built in VISION and bringing these facilities offline for a short period of time.

1.5 Thesis Organization

The work presented in this thesis will describe the methodology developed from this research and analyze advanced fuel cycle scenarios using the VISION model. The methodology, presented in Chapter 2, will describe how reactors and their support facilities are built in accordance with the proper demand functions. Following the build logic, the methodology will then describe upset scenarios and their respective mitigation strategies. The results from this improved building logic and upset event analysis will be presented in Chapter 3 and discussed in Chapter 4 in order to provide readers with a better understanding of advanced fuel cycles. Chapter 5 concludes the thesis, presenting conclusions and recommendations for future work.

2 Methodology

2.1 Methodology Overview

This methodology introduces a mathematical model for the decision making logic of when to start construction of new fuel cycle facilities and recovery strategies for an upset event involving a facility for a stage of a fuel cycle. An upset event is defined as a deviation from the planned operation of facilities, e.g. delay in construction of new facilities or decrease of expected availability factor. The model also facilitates the incorporation of mathematical optimization capabilities.

The mathematical model is based upon a demand-supply model, where facilities for one or more stages of the fuel cycle create demand which is serviced by the supply produced by facilities for another stage. The overall driver triggering the demand is electrical energy growth that is expected over the next 100 years. The second controlling function is that the fuel for Fast Burner Reactors (FBR) comes primarily from Light Water Reactor spent fuel, so the light water reactors must produce enough spent fuel to supply the operating FBRs.

To further explain the model by way of example, for a closed fuel cycle, the future electrical energy demand will require increased supply of electrical energy, which if supply is not adequate (always the case since nuclear power plants assumed to operate at Capacity Factor = Availability Factor unless an upset event occurs) will require new nuclear power plants to be built, which will result in an increased demand for fuel fabrication services, which if supply and usable inventory is not adequate will require new fuel fabrication plants to be built, which will result in an increased demand for separation services, which if supply and usable inventory is not adequate will require new separation plants to be built, which will result in an increased demand for spent fuel, which if supply and usable inventory is not adequate will require new nuclear power plants to be built. Note that a circular logic has developed, where we started with building new nuclear power plants due to electrical demand and return to this at the end due to spent fuel demand. This implies that some decisions, e.g. mix of Light Water Reactor multiple fuels (LWRmf) (note: multiple fuels means UOX, MOX or IMF) and Fast Burner/Breeder Reactor (FBR) or conversion ratio of FBR, must be made such that the starting and ending states are consistent. In order to prevent a mismatch of fuel available for advanced reactors at their startup, a predicted spent fuel calculation must be performed at the time of ordering reactors that will tell the system how much spent fuel is available for use in advanced reactors. The circular logic is shown below in Figure 2-1.

In the circular logic shown in Figure 2-1, the current time (t = 0) is where the decisions will be made based on the projection of the energy required. The model will project out a certain number of years, in this case 15 years, and decide the appropriate mix of reactors and the necessary number of support facilities. The mix of reactors will be determined by a spent fuel prediction and by a user controlled deployment percentage.

2.1.1 Basic Equations for Supply and Demand

2.1.1.1 Future Demand for Supply Facilities

The future demand function will allow the simulation to determine the facility needs of the fuel cycle and make the appropriate build decision at the current time, *t*, so that there is enough time to build a supply facility and produce the services that other facilities demand.

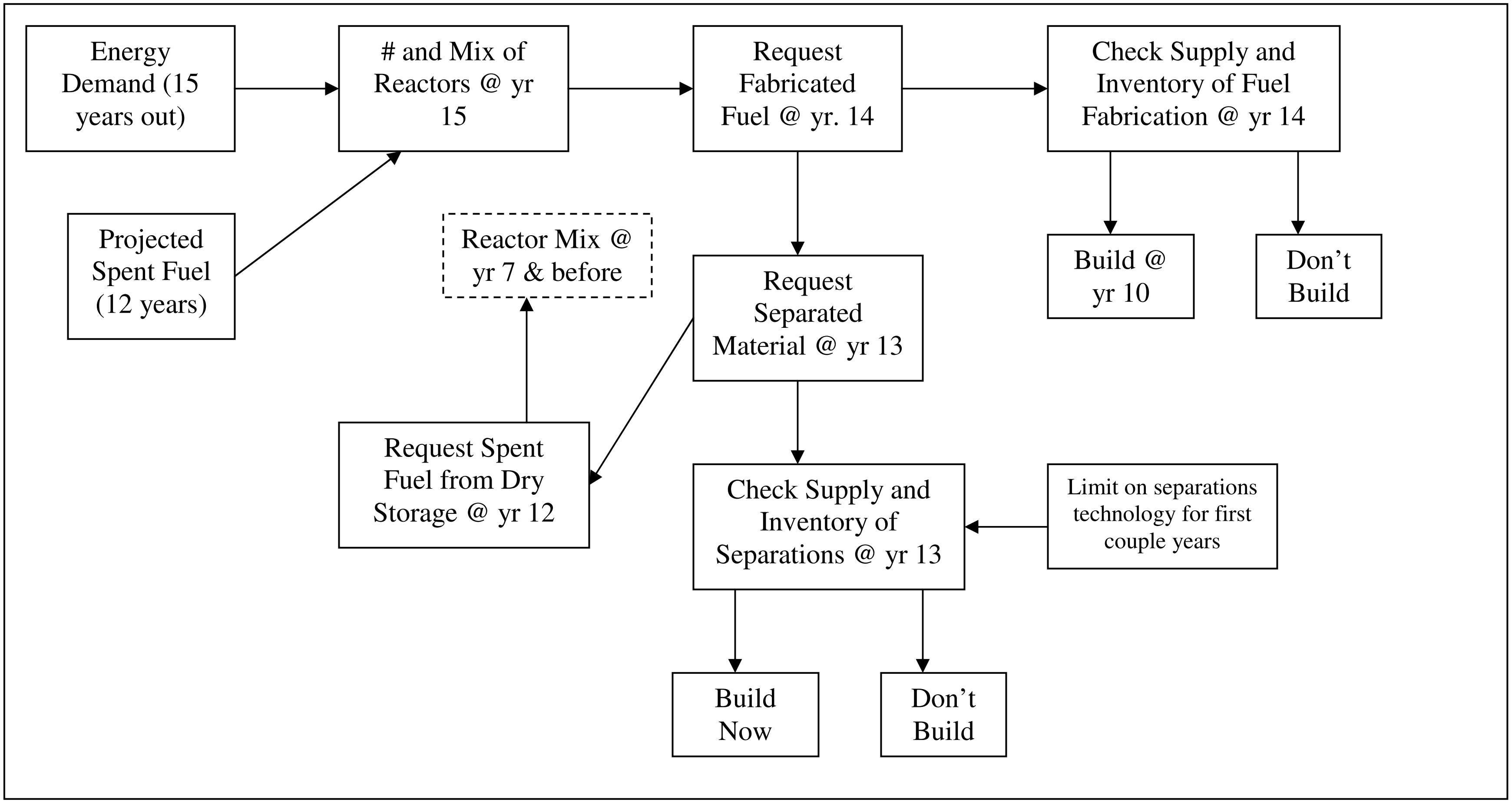

Figure 2-1: Methodology for building reactors and their required support facilities

This demand function looks a certain number of years into the future ($t+\Delta t^x$), where t is the current time and Δt^x is the time it takes to license and build a supply facility of type *x*. The demand function also projects out to the year t', where t' is the year that demand facilities utilize the services provided by supply facilities.

The demand function is written out in Equation 2.1.

$$D^x_{t+\Delta t^x} = \sum_{y,t' \geq t+\Delta t^x} \gamma^{y \to x}_{t' \to t+\Delta t^x} N^y_{t'} C^y_{t'} \qquad \text{Equation 2.1}$$

D^x_t - Demand rate for time period t' for service or product of facility of type *x* based on the number of type *y* facilities that are operating at time period t'.

$N^y_{t'}$ - Number of operating facilities of type *y* at time t' that require the service from type *x* facility. This includes planned facilities and those now operating at t' who will continue to operate at t'.

$C^y_{t'}$ - Expected capacity factor for facilities of type *y* at time t'.

$\gamma^{y \to x}_{t' \to t+\Delta t^x}$ - Conversion factor that converts the demand rate for time period t' for service or product of facility *y* into a demand rate for time period $t+\Delta t^x$ for service or product of facility *x* that will service facility *y*. It is assumed that the product or service of facility *x* can be produced over one time period, e.g. one year, which implies $\gamma^{y \to x}_{t' \to t+\Delta t^x}$ only takes on a non-zero value for one value of t' when $t' - (t+\Delta t^x) =$ time to start offering/production of service/product of facility *x* to have completed, i.e. manufactured + delivered + stored, for facility *y*.

2.1.1.2 Rated Supply

The supply function takes the number of operating facilities and their respective availabilities and determines how much available supply of a certain service via production there is in the system. The supply function is as follows:

$$S^x_{t+\Delta t^x} = \beta^x N^x_{t+\Delta t^x} A^x_{t+\Delta t^x} \qquad \text{Equation 2.2}$$

$S^x_{t+\Delta t^x}$ - Rated supply rate of product at $t+\Delta t^x$ that can be produced by type *x* facility.

$N^x_{t+\Delta t^x}$ - Number of operating facilities of type *x*, including planned facilities and those now operating who at $t+\Delta t^x$ will continue to operate.

$A^x_{t+\Delta t^x}$ - Availability factor of facility type *x* that is in operation.

β^x - Converts the number of facilities of type *x* into a supply rate of type *x*.

In order to get the rated supply, the availability $A^x_{t+\Delta t}$ is assumed constant at its full rated availability, A^x, throughout the simulation and not changing with time.

2.1.1.3 Current Demand Function

In order to get the current demand, or the demand for services that the system is currently requesting, simply take Equation 1 and set Δt^x equal to zero. This will make the demand function equal to the current demand to produce a product or service. This demand will be labeled $\hat{D}^x_t$ for further use in the methodology.

$$\hat{D}^x_t = \sum_{y,t'\geq t} \gamma^{y\to x}_{t'\to t} N^y_{t'} C^y_{t'} \qquad \text{Equation 2.3}$$

2.1.1.4 Current Supply Function

In order to get the current supply, simply set the Δt^x in Equation 2 equal to zero. This will cause the equation to only use the facilities that are in operation at the current time *t*. The current supply will be labeled $\hat{S}_t^x$ for further use in the methodology.

$$\hat{S}_t^x = \beta^x N_t^x A_t^x \qquad \text{Equation 2.4}$$

2.1.1.5 Actual Output from Facilities

The actual available output of facilities is based on the capacity factor of the facilities of type *x*. The capacity factor will change automatically for the system as new facilities come online and start requesting services.

$$\mathrm{O}_t^x = \beta^x N_t^x C_t^x \qquad \text{Equation 2.5}$$

O_t^x - Actual output of facility of type *x* at time *t*.

C_t^x - Capacity factor for facilities of type *x* at time *t*.

2.2 Reactor Order Methodology

2.2.1 Projected Energy Growth Rate

In order to implement this methodology a projected energy demand growth and spent fuel prediction had to be calculated in order to determine the number and type of reactors that can come online. The model will look ahead for a variable number of years (this should be the longest construction time of all of the facilities plus time to manufacture, deliver and store, in this case 20 years) and calculate supply and demand for reactors, fuel fabrication and separations. At the beginning of the simulation, before the first time step, the model calculates the energy growth for every year of the simulation plus the number of years the model is looking ahead. The growth function is as follows:

$$E_t = E_{t-1} * (1 + p_t / 100) \qquad \text{Equation 2.6}$$

where E_t in Equation 2.6 is the electric demand at year t and p_t is the growth percentage at year t. When the function reaches the last growth rate p_{100} provided by the input, it will hold that value in order to project out values beyond the 100 year time period.

The next step is to then calculate the number of reactors that can come online based on the growth rate. During the initial look ahead time, Δt_{look} (default look ahead time is 20 years), the model will only build LWRmf reactors because it is assumed that there will not be any FBRs deployed before the initial look ahead time. This is necessary to assure that the fuel cycle facilities needed to support a FBR are available when FBRs are deployed. The initial reactors are built in a Visual Basic function, so that at the beginning of the simulation the model will know how many reactors need to come online and when they need to come online. These reactors are then sent to an Order Rate Array ($\overline{RO}$) where they will be stored and called upon when it is time to order reactors. As the model starts, the simulation will progress forward with the t variable moving one year out for each year of the simulation. Reactors will be built based on the energy gap and the spent fuel prediction as a function of time.

2.2.2 Spent Fuel Prediction for 1-Tier Case

The 1-tier case is based upon only doing LWR Spent Fuel (LWRsf) recycle in FBRs. In order to know how many FBRs the simulation can build, there must be a method for predicting how much LWR spent fuel will be available for use in a FBR, since the FBR conversion ratio is less than 1.0 given their purpose of consuming LWRsf. The spent fuel predictor will be used to calculate how much LWRsf a LWR and LWRmf reactor will generate over its lifetime. Given the look ahead time, Δt_{look}, the point at which the simulation will calculate the spent fuel from ordered reactors is $t + \Delta T_{look}$, where ΔT_{look} is given as follows:

$$\Delta T_{look} = \Delta t_{look} - \left(\Delta t_{ws}^{LWRmf} + \Delta t_{1FBR} + \Delta t_{S}^{FBR} + \Delta t_{FF}^{FBR}\right) = 3yr^{*} \qquad \text{Equation 2.7}$$

Subtracting out the wet storage time, separation time and fuel fabrication time (Δt_{ws}^{LWRmf}, Δt_{S}^{FBR} and Δt_{FF}^{FBR} respectively) in Equation 2.7 allows the model to determine what spent fuel will be available for placement in a reactor at Δt_{look} years ahead. However, this is still not enough time to predict how much fuel will be available for an initial FBR core load because one reload batch of LWRsf is not enough to build one initial core for a FBR. In order to make sure there is an adequate amount of spent fuel available for a FBR core, the time it takes to accumulate the required amount of spent fuel must also be subtracted from the look-ahead time. This is the Δt_{1FBR} in the Equation 2.7 which is calculated by using Equation 2.8:

$$\Delta t_{1FBR} = \frac{\left(CL_{FBR} * w\%_{FBR_{Fresh}}^{Pass1}\right)}{\left(FL_{LWRmf}^{Pass\#} * w\%_{LWRsf}^{Pass\#}\right)} \qquad \text{Equation 2.8}$$

In Equation 2.8 the $FL_{LWRmf}^{Pass\#}$ is the reactor fuel load per year for a LWRmf reactor and the CL_{FBR} variable is the core load for a FBR. The $w\%_{FBR_{Fresh}}^{Pass1}$ variable includes the weight percents of the control isotopes in the fresh fuel for a FBR. All of the $w\%$ s come from the fresh fuel and spent fuel recipes that are imported to the model. The LWRsf spent fuel weight percent, $w\%_{LWRsf}^{Pass\#}$, is for the same control isotopes as that for the FBR fresh fuel. It is written to be dependent on the number of thermal recycle passes, so if MOX fuel for a 2-tier case is used this will be taken into account. As noted above, all of the isotopes are not used;

[*] Number will change based on input from user. Three years is used as an example for reader clarity.

only the FR Pu Control isotopes are used. The FR Pu Control switch tells the system which elements are the dominating fuel elements. Options for this control switch are shown in Table 2-1.

Table 2-1: Options for the FR Pu Control Switch

FR Pu Control Switch	Isotopes Used
0	Min(Pu^{239}, Pu^{240}, Pu^{241})
1	Pu^{239}
2	Pu^{240}
3	Pu^{241}
4	Total TRU (NP237 - Cf 252)
5	Total Pu

Therefore, in Equation 2.8 if the FR Pu Control switch is set to 4, the equation will be as follows:

$$t_{1FBR} = \frac{\left(CL_{FBR} * w\%_{FBR_{Fresh}}^{Pass1}[TRU]\right)}{\left(FL_{LWRmf}^{Pass\#} * w\%_{LWRsf}^{Pass\#}[TRU]\right)} \qquad \text{Equation 2.8a}$$

At the start of the simulation the spent fuel predictor will start at the 3rd point in the $\overline{RO}$ array (corresponding to year 2003) because the ΔT_{look} is equal to 3 and t = 2000 initially. The spent fuel predictor will move forward by one year each year the simulation progresses. Each time a LWRmf reactor is ordered the spent fuel predictor calculates spent fuel that will be generated over the reactor's lifetime for a FBR starting up at $t + \Delta t_{look}$ using Equation 2.9:

$$SF_{LWRmf,t+\Delta t_{look}} = RO_{LWRmf,t+\Delta T_{look}} * (FL_{LWRmf} * (\Delta t_{LWRmf}^{Lifetime} - 1) + CL_{LWRmf}) * w\%_{LWRsf} \qquad \text{Equation 2.9}$$

where the $\overline{RO}_{LWRmf,t+\Delta T_{look}}$ is the reactor order rate for LWRmf reactors at the adjusted look ahead time and $\Delta t_{LWRmf}^{Lifetime}$ is the reactor lifetime for a LWRmf reactor. The spent fuel is then sent to an Unmortgaged Spent Fuel Stock whose mass is determined using Equation 2.10:

$$\overline{uSF}_t = \overline{uSF}_{t-1} + SF_{LWRmf,t+\Delta t_{look}} \qquad \text{Equation 2.10}$$

where it will reside until fast reactors are ordered. The code also performs the same spent fuel calculation if reactors are ordered between year 2000 and 2003 as well as the legacy reactors that are already operating. The Legacy Spent Fuel (spent fuel generated before the simulation begins in year 2000) can also be added to the $\overline{uSF}_t$ if the user would like to use Legacy SF in the simulation.

2.2.3 Spent Fuel Prediction for 2-Tier Case

The spent fuel calculation for the 2-Tier Case is shown in the Appendix because none of the results to be presented are with a 2-Tier case.

2.2.4 Ordering FBR Reactors

Before a fast reactor can be ordered there has to be some assurance that there will be enough LWRsf fuel available for the reactor over its lifetime. This assurance will come from using the predicted amount of available spent fuel from the $\overline{uSF}_t$ and calculating the amount of LWRsf that a FBR will consume over its entire lifetime. FBRs will use spent fuel based on the reactor's conversion ratio, or the fraction of transuranics that are consumed over what is produced. If a reactor has a low conversion ratio, then it will be consuming more transuranics than it produces and will require more LWRsf to keep it operational. Higher conversion ratios require less LWRsf and a conversion ration equal to or greater than 1 will require no additional LWRsf. For these reasons it is important to know how much spent fuel is available and how much a FBR will be requiring over its lifetime.

2.2.4.1 Fraction of FBR Fuel Coming from LWR

The amount of Light Water Reactor Spent Fuel (LWRsf) that a FBR will consume over its lifetime is a complicated calculation because each pass of FBR fuel requires less and less LWRsf until the FBR reaches equilibrium. The basis of this calculation is to take the difference between the FBR fresh fuel for a new pass and subtract it from the FBR spent fuel from the previous pass. This calculation must also take into account the wet fuel storage time, separation time and fuel fabrication time of FBR fuel because this will determine how long fuel sits idle before becoming the next pass of fuel. The difference will determine how much LWRsf a FBR will require. Figure 2-2 below gives a diagram of the timeframes of the calculation.

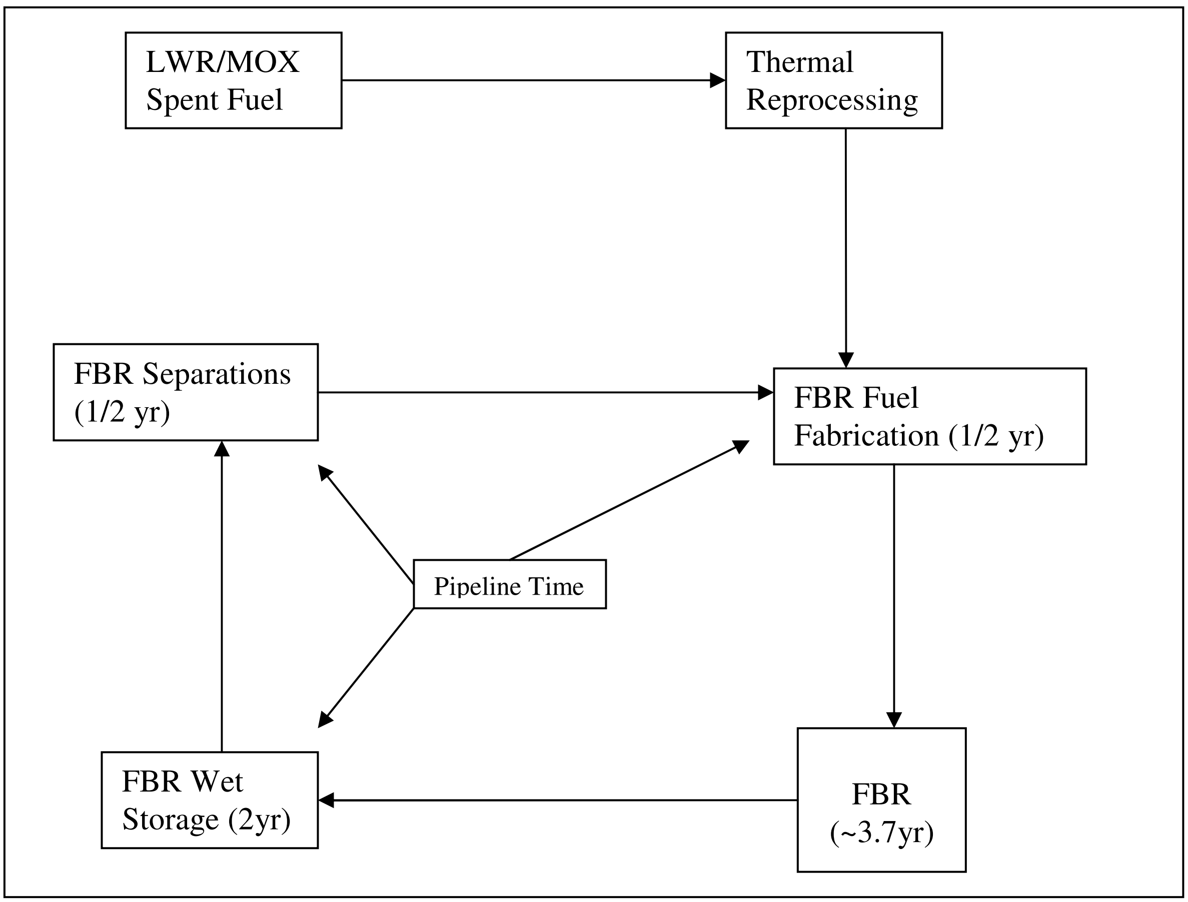

Figure 2-2: Diagram for the amount of time its takes fuel to move to the next pass

The following equations are used to describe the amount of time fuel spends in the various stages of the fuel cycle.

$$\Delta t_{pipeline}^{FBR} = \Delta t_{ws}^{FBR} + \Delta t_{S}^{FBR} + \Delta t_{F}^{FBR} \quad \text{Equation 2.11}$$

$$\Delta t_{reactor}^{FBR} = \Delta t_{cycle}^{FBR} * \# B^{FBR} \qquad \text{Equation 2.12}$$

$$\Delta t_{around}^{FBR} = \Delta t_{pipeline}^{FBR} + \Delta t_{reactor}^{FBR} \qquad \text{Equation 2.13}$$

<u>Total FBR Fuel Required</u>

$$\begin{aligned} F_{Total}^{FBR} = CL_{FBR_{Fresh}}^{pass1} * w\%_{FBR_{Fresh}}^{pass1} + \\ \Delta t_{pipeline} * FL_{FBR_{Fresh}}^{pass1} * w\%_{FBR_{Fresh}}^{pass1} + \\ \Delta t_{around} * FL_{FBR_{Fresh}}^{pass2} * w\%_{FBR_{Fresh}}^{pass2} + \\ \Delta t_{around} * FL_{FBR_{Fresh}}^{pass3} * w\%_{FBR_{Fresh}}^{pass3} + \\ \Delta t_{around} * FL_{FBR_{Fresh}}^{pass4} * w\%_{FBR_{Fresh}}^{pass4} + \\ \Delta t_{around} * FL_{FBR_{Fresh}}^{pass5} * w\%_{FBR_{Fresh}}^{pass5} + \\ \left(\Delta t_{lifetime}^{FBR} - 4 * \Delta t_{around} - \Delta t_{pipeline} - 1\right) * FL_{FBR_{Fresh}}^{pass5} * w\%_{FBR_{Fresh}}^{pass5} \end{aligned} \qquad \text{Equation 2.14}$$

The F_{Total}^{FBR} variable in Equation 2.14 has units of Kt/reactor for control isotopes and calculates the total amount of Kt of control isotopes that a fast reactor will require over its lifetime. The variable includes the five different passes of separation. Once the fuel reaches pass 5 all of the fuel remains in pass 5 since the reactor is assumed to be in equilibrium.

<u>Total LWRsf Required</u>

$$\begin{aligned} F_{Total}^{LWRsf} = CL_{FBR_{fresh}}^{pass1} * w\%_{FBR_{Fresh}}^{pass1} + \\ \Delta t_{pipeline} * FL_{FBR_{Fresh}}^{pass1} * w\%_{FBR_{Fresh}}^{pass1} + \\ \Delta t_{around} * \left(FL_{FBR_{Fresh}}^{pass2} * w\%_{FBR_{Fresh}}^{pass2} - FL_{FBR_{SF}}^{pass1} * w\%_{FBR_{SF}}^{Pass1}\right) + \\ \Delta t_{around} * \left(FL_{FBR_{Fresh}}^{pass3} * w\%_{FBR_{Fresh}}^{pass3} - FL_{FBR_{SF}}^{pass2} * w\%_{FBR_{SF}}^{Pass2}\right) + \\ \Delta t_{around} * \left(FL_{FBR_{Fresh}}^{pass4} * w\%_{FBR_{Fresh}}^{pass4} - FL_{FBR_{SF}}^{pass3} * w\%_{FBR_{SF}}^{Pass3}\right) + \\ \Delta t_{around} * \left(FL_{FBR_{Fresh}}^{pass5} * w\%_{FBR_{Fresh}}^{pass5} - FL_{FBR_{SF}}^{pass4} * w\%_{FBR_{SF}}^{Pass4}\right) + \\ \left(\Delta t_{lifetime}^{FBR} - 4 * \Delta t_{around} - \Delta t_{pipeline}\right) * \left(FL_{FBR_{Fresh}}^{pass5} * w\%_{FBR_{Fresh}}^{pass5} - FL_{FBR_{SF}}^{pass5} * w\%_{FBR_{SF}}^{pass5}\right) \end{aligned} \qquad \text{Equation 2.15}$$

The variable F_{Total}^{LWRsf} in Equation 2.15 has units of Kt/reactor for control isotopes and calculates the amount of Kt of control isotopes that a fast reactor will need from LWRsf. In the first couple of years all of the FR fuel comes directly from LWRsf because FBRsf has not made it through wet storage, separations and fabrication. Once the first batch of pass 1 fuel makes it through separations, the new reload batch will be a combination of the FBRsf and the LWRsf. The amount of LWRsf is simply the difference between the FBR Fresh Fuel and the FBR Spent Fuel from the previous pass. This is calculated for each of the passes because the fuel composition changes after each pass. The variable F_{Total}^{LWRsf} in Equation 2.15 will be used to determine how many FBR can come online at the look ahead time by using Equation 2.16:

$$\#FBR_{SF,t+\Delta t_{look}} = \frac{\overline{SF}_t[PuControl]}{F_{Total}^{LWRsf}[PuControl]} \qquad \text{Equation 2.16}$$

where $\overline{SF}_t$ denotes the available spent fuel. When reactors are ordered, fuel in the amount of F_{Total}^{LWRsf} per reactor ordered is added to a Mortgaged Spent Fuel Stock, $\overline{MSF}_t$.

$$\overline{MSF}_t = \overline{MSF}_{t-1} + RO_{FBR,t+\Delta t_{look}} * F_{Total}^{LWRsf} \qquad \text{Equation 2.17}$$

The available spent fuel is determined as follows:

$$\overline{SF}_t = \overline{uSF}_t - \overline{MSF}_t \qquad \text{Equation 2.18}$$

2.2.4.2 Ordering of Reactors

FBRs are ordered using two functions to control the ordering rate. The first function is based on the user defined reactor percent distribution and the energy gap, and the second function is based on the maximum number of FBRs for which LWRsf can support. When reactors are ordered it is the minimum value of the two functions that determines how many reactors can be built. The first function based on energy and percent distribution is:

$$\# FBR_{E_{t+\Delta t_{look}}} = Ceiling\left(\frac{\left(E_{t+\Delta t_{look}} - E^{reactors}_{t+\Delta t_{look}}\right) * \text{'FBR \% Distribution'}_{t+\Delta t_{look}}}{\text{Rp}^{\text{FBR}}}, 1 << reactor >> \right)$$

Equation2.19

In Equation 2.19 the $\left(E_{t+\Delta t_{look}} - E^{reactors}_{t+\Delta t_{look}}\right)$ is the energy gap based on the look ahead energy prediction from Equation 2.6 and the electricity being produced from online reactors and reactors that have been ordered by the prediction, $E_{t+\Delta t_{look}}$. Rp^{FBR} denotes the full power electrical power rating per fast reactor. The ceiling function in Equation 2.19 ensures that reactors are built in integer units and no partial reactors are ordered. The 'FBR % Distribution' is a user input to the model, so the user can specify the percentage of FBRs the system will order that specific year. The actual ordering function is as follows:

$$\overline{RO}_{FBR,t+\Delta t_{look}} = Min\left(\# FBR_{E_{t+\Delta t_{look}}}, \# FBR_{SF,t+\Delta t_{look}}\right) \quad \text{Equation 2.20}$$

The reactors that are ordered are sent to the order rate array $\overline{RO}$ in the FBR element that is Δt_{look} years from the current time *t*. The ordering function ensures that the model will not exceed the energy demand by ordering too many reactors, and that the number of reactors will not exceed the amount that can be supported by the spent fuel. The user has a lot of control with this ordering function by changing the 'FBR % Distribution' in Equation 2.19. This value can be lowered to minimize the number of FBRs being ordered or it can be maximized to ensure that the maximum numbers of FBRs are built and the LWRsf inventory is minimized.

2.2.5 Ordering LWR and LWRmf Reactors

At the beginning of the simulation and for the first several time steps only LWRmf reactors are ordered; however, when FBRs enter the mix the algorithm for determining

LWRmf ordering rate must be introduced. The first equation for building LWRmf reactors is based solely on the electric power gap and the 'LWRmf % distribution'. This equation is as follows:

$$\#LWRmf_{E_{t+\Delta t_{look}}} = Ceiling\left(\frac{\left(E_{t+\Delta t_{look}} - E^{reactors}_{t+\Delta t_{look}}\right) * 'LWRmf\ \%\ Distribution'_{t+\Delta t_{look}}}{Rp^{LWRmf}}, 1 << reactor >>\right)$$

Equation 2.21

The 'LWRmf % Distribution' in Equation 2.21 has equivalent meaning as the 'FBR % Distribution' in Equation 2.19, with the sum of the LWRmf, FBR and LWR % Distributions adding up to 100 (LWR reactors are not normally built by the model, so this value is usually 0). Both the electric power gap and the 'LWRmf % Distribution' are calculated at the year Δt_{look} years ahead from the current year *t*. When FBR enter the mix, another equation is added to build LWRmf reactors when FBR cannot meet the energy demand. The extra LWRmf equation is as follows:

$$\#FBR_{Not,t+\Delta t_{look}} = Max\left(0 << reactor >>, \#FBR_{E_{t+\Delta t_{look}}} - \overline{RO}_{FBR,t+\Delta t_{look}}\right) \qquad \text{Equation 2.22}$$

$$\#LWRmf^{+}_{t+\Delta t_{look}} = Ceiling\left(\frac{\#FBR_{Not,t+\Delta t_{look}} * Rp^{FBR}}{Rp^{LWRmf}}, 1 << reactor >>\right) \qquad \text{Equation 2.23}$$

In Equation 2.22 the $\#FBR_{Not,t+\Delta t_{look}}$ are the number of FBR that cannot be ordered because there is not enough spent fuel available, and the $\#LWRmf^{+}_{t+\Delta t_{look}}$ in Equation 2.23 are the LWRmf reactors that are built to meet the energy demand that the FBRs cannot fulfill. The sum of the reactors from the Equation 2.21 and Equation 2.23 are added to the $\overline{RO}$ at the $t+\Delta t_{look}$ date. The equation for this ordering is:

$$\overline{RO}_{LWRmf,t+\Delta t_{look}} = \#LWRmf^{+}_{t+\Delta t_{look}} + \#LWRmf_{E_{t+\Delta t_{look}}} \qquad \text{Equation 2.24}$$

2.3 Facility Order Methodology

2.3.1 Inventory

For certain types of facilities it may be possible to accumulate an inventory of product, e.g. ore, reprocessed material, UF_6, and standardized first cores that are not yet plant specific. In this case, such facilities could operate at maximum capacity, i.e. availability, until a certain limit is reached (could be limited by storage capability or investment limitation). Equation 2.25 defines how an inventory will be treated in the model. In this equation the demand function is from Equation 2.1 and the supply function is from Equation 2.2.

$$I_t^x = \min\left[\left(S_{t-1}^x - D_{t-1}^x\right) + I_{t-1}^x, \left(I_t^x\right)_{Max}\right] \qquad \text{Equation 2.25}$$

A portion of inventory can be set aside into a bank reserved for emergency recovery. This emergency bank is denoted by $\left(I_t^x\right)_{Bank}$. This implies the usable inventory to meet normal demand is given by Equation 2.26:

$$\left(I_t^x\right)_{Usable} = I_t^x - \left(I_t^x\right)_{Bank} \qquad \text{Equation 2.26}$$

2.3.2 Build Logic

The usable inventory can be used to defer the construction of new type *x* facilities.

$$S_{t+\Delta t^x}^x + \left(I_{t+\Delta t^x}^x\right)_{Usable} \geq D_{t+\Delta t^x}^x \qquad \text{Equation 2.27a}$$

$$S_{t+\Delta t^x}^x + \left(I_{t+\Delta t^x}^x\right)_{Usable} < D_{t+\Delta t^x}^x \qquad \text{Equation 2.27b}$$

If Equation 2.27a is true in the model, then there is no need to start building a new *x* facility at time *t*; however, if Equation 2.27b is true then the model will start building a new *x* facility at time *t*. The predicted supply and demand values in Equation 2.27a and 2.27b come from the predicted supply and demand functions in Equations 2.1 and 2.2. Since the Δt_{look} value is greater than the Δt^x for any facility, all of the facilities should be able to begin construction and operation just before their services are required by the demand drivers. For types of facilities that cannot accumulate inventory because the product is reload specific, $\left(I_t^x\right)_{Max} = 0$; causing $I_t^x = 0$, $\left(I_t^x\right)_{Bank} = 0$ and $\left(I_t^x\right)_{Usable} = 0$. This implies that Equations 2.27a and 2.27b will work under any normal circumstance.

When building LWRsf aqueous separation facilities, it is necessary to bring these facilities online a certain number of years early in order to account for the first couple of years a FBR will be requesting fuel. During the first several years of operation for a FBR, all of the fuel for the reactor will come directly from LWRsf via aqueous separations. Then after this time period fast reactor fuel separations will start up and the demand for separated material from LWRsf will go down. In order to meet this early demand a lead time (Δt_{lead}) will be added to the Δt^x for separation facilities in Equations 2.27a and 2.27b since the actual construction time will not be altered the addition of this time will allow for separation facilities to be built and operate early, allowing for enough material to accumulate in the separated material inventory for the initial demand of FBRs. This lead time could vary based on the number of FBRs that come online in any given year; however, currently the model only can treat a constant lead time. To account for this, several simulations will be run with a variable lead time and separation facility size in order to determine the best combination for any given scenario.

2.4 Delay and Upset Scenario Methodology

2.4.1 Demand Upset Scenario

If demand decreases due to changes in availability or construction delay, the system can tolerate this easily. The upset operating demand will be denoted by $\widehat{D}_t^x$. Equation 2.28 shows the scenario where there is a decreased future demand that becomes less than the predicted future supply and inventory.

$$S_{t+\Delta t}^x + \left(I_{t+\Delta t}^x\right)_{Usable} \geq \widehat{D}_{t+\Delta t}^x \text{ for } \Delta t = 1, 2, \ldots, \left[(\Delta t^x + \Delta t_d(1-\delta_d)) - 1\right] \qquad \text{Equation 2.28}$$

Equation 2.32 holds true if a specific Δt and a new *x* facility is already under construction that started licensing and construction at $t + \Delta t - [\Delta t^x + \Delta t_d(1-\delta_d)]$. During this situation the model will suspend construction of some of these facilities until $\hat{S}_{t+\Delta t}^x + \left(I_{t+\Delta t}^x\right)_{Usable} < \widehat{D}_{t+\Delta t}^x$, where $\hat{S}_{t+\Delta t}^x$ denotes the change in supply due to suspended construction. The Δt_d variable is the additional construction time that will continue to increase as long as the supply and inventory are greater than the decreased demand. Currently the model has a maximum value of 5 years for the Δt_d variable. The δ_d is a binary variable that equals 1 when there is no necessary delay and 0 when a delay is needed. In the VISON model the δ_d is represented by a true/false statement, that represents the situation of a decreased demand. As formulated, all *x* facility construction initiated at the same time would be suspended if necessary. If multiple facilities are under construction, then the stock and flow model of system dynamics will allow this delay to apply to only a subset of the facilities. This will ensure that supply and demand will be met when the upset event is over.

2.4.2 Predicted Supply Upset Scenario

In addition to the demand upset events, there are also supply upset events. In the event of an upset scenario the supply and inventory will decrease (note the decreased supply and inventory is denoted $\hat{S}_t^x$ and $\left(\hat{I}_t^x\right)_{Usable}$). Equations 2.29a and 2.29b shows the relationships that will govern this type of event.

$$\hat{S}_{t+\Delta t^x}^x + \left(\hat{I}_{t+\Delta t^x}^x\right)_{Usable} < D_{t+\Delta t^x}^x \qquad \text{Equation 2.29a}$$

$$S_{t+\Delta t^x}^x + \left(I_{t+\Delta t^x}^x\right)_{Usable} \geq D_{t+\Delta t^x}^x \qquad \text{Equation 2.29b}$$

Equation 2.29a shows the predicted upset supply and inventory dropping below the predicted demand, while in Equation 2.29b the rated supply and inventory are greater than the demand. If Equation 2.29a is true, in this event no new x facilities will be built because this is a temporary upset event.

2.4.3 Current Supply Upset Scenario

If the current "upset" supply and the total inventory are greater than the demand,

$$\hat{S}_t^x + I_t^x \geq D_t^x \qquad \text{Equation 2.30}$$

then use the total inventory as necessary. If the condition exists where the current "upset" supply and total inventory do not meet the current demand,

$$\hat{S}_t^x + I_t^x < D_t^x \qquad \text{Equation 2.31}$$

then move through recovery strategies, denoted by $\left(\Delta S_t^x\right)_i$ and $\left(\Delta D_t^x\right)_i$ until:

$$\hat{S}_t^x + I_t^x + \sum_{i \in R_S^x} \left(\Delta S_t^x\right)_i \geq D_t^x - \sum_{i \in R_D^x} \left(\Delta D_t^x\right)_i \qquad \text{Equation 2.32}$$

where R_S^x and R_D^x denote supply and demand recovery strategies, respectively, which are added to or subtracted from, respectively, in order of priority until the "≥" inequality in the above equation is satisfied for the first time. In the order of recovery strategies the supply recovery strategies are used first, and if found inadequate, demand recovery strategies are also used. The lead time on building facilities and the size of facilities that are built will also play a major role for mitigating the negative affects of this upset scenario.

Supply Recovery Strategies (R_S^x)

1. Increase the capacity factor of *x* facility in order to use slack in the system (automatic response).
2. Use substitute supplies and inventory types, e.g. U^{235} and Pu^{239} stockpile from commercial and weapons programs, for *x* type.
3. Delay retirement of *x* facilities.

Demand Recovery Strategies (R_D^x)

1. Delay construction of new *y* facilities.
2. Decrease capacity factor of operating *y* facilities.
3. Retire older *y* facilities earlier than planned.

3 Results

3.1 Results from Revised Reactor Build Methodology

<u>Old Reactor Build 1-Tier</u>

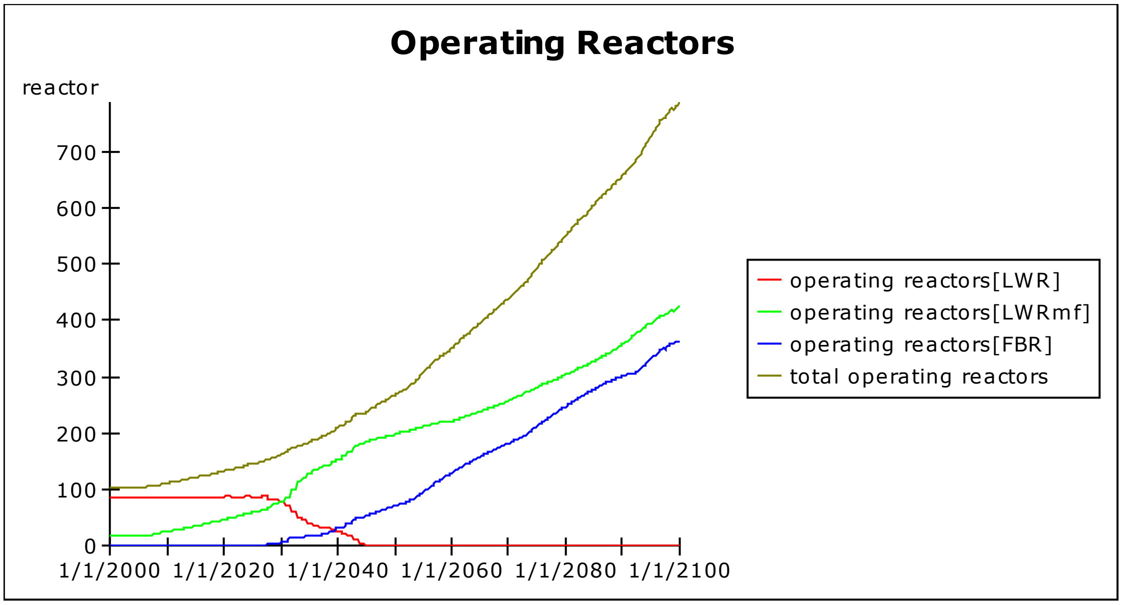

Figure 3-1: Operating Reactors in VISION 2.2.2 1-Tier

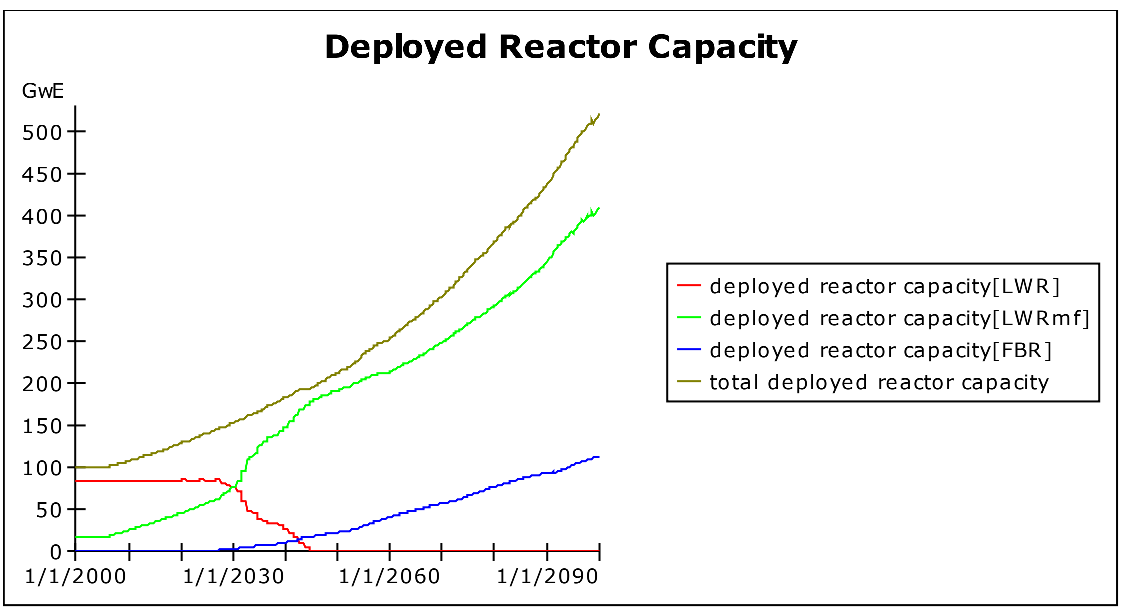

Figure 3-2: Deployed Reactor Capacity for VISION 2.2.2 1-Tier

The graphs presented in Figure 3-1 and Figure 3-2 are produced from VISION Version 2.2.2 that was released in the Spring of 2008. The initial electric demand level is set at 100GWe and the growth rate is set to 1.8% starting in year 2007 and used throughout the remainder of the simulation and results. The GWe output for each reactor is as follows, 1.07GWe for LWRs, 1.07GWe for LWRmf reactors and 0.360GWe for FBRs. These numbers will also be used throughout the remainder of the results. FBRs are introduced in the simulation starting in year 2025 and their build rate is ramped up to 100% of the electrical energy demand, unless there is not enough separated product available to support new FBRs. If there is not enough separations capacity at the current time then the simulation will build LWRmf reactors. The maximum GWe in Figure 3-2 is 520.35GWe.

New Reactor Build 1-Tier

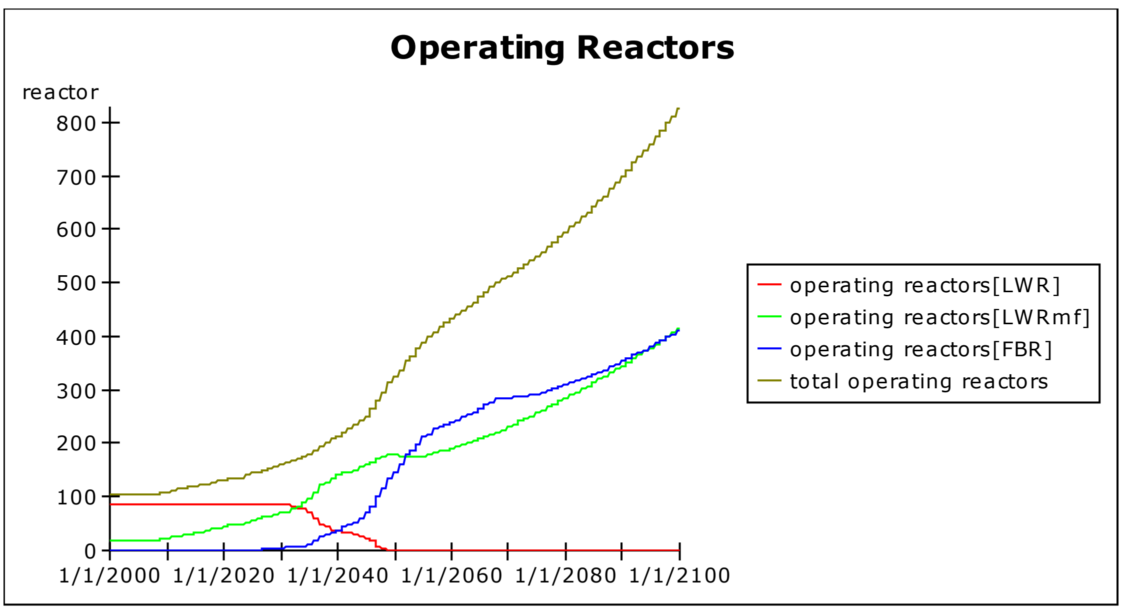

Figure 3-3: Operating Reactors for New Methodology 1-Tier

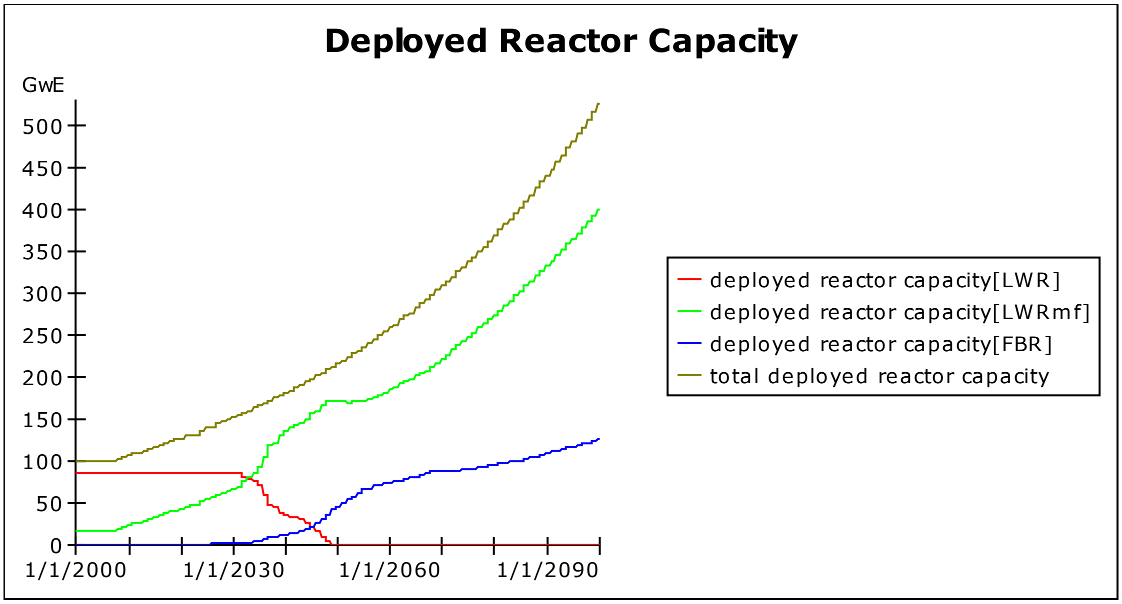

Figure 3-4: Deployed Reactor Capacity for New Methodology 1-Tier

The graphs in Figure 3-3 and Figure 3-4 show the number of reactors operating and the deployed reactor capacity for a 1-Tier case with the revised reactor build methodology. The maximum GWe in Figure 3-4 is 526.07GWe. In this case the inventories were set to zero. The main difference between the two reactor build logics is that the old logic will build FBRs based on what separations capacity is operating at the current time and the new logic will build FBRs based on a predicted amount of spent fuel in the system. This new logic will then build the required separations and fuel fabrication facilities to meet this demand, not the other way around as it is done with the old logic. This forecasting method allows the simulation to rapidly build FBRs in order to reach an equilibrium of FBR and LWRmf reactor build starting around 2090 (shown in Figure 3-3). The old logic does not reach equilibrium because the FBRs are always trying to catch up with the separated material which only looks at the current amount with no look ahead (shown in Figure 3-1).

3.2 Results from Facility Ordering Methodology

Results presented in this section will detail the perturbations of LWRsf separation facility size, lead time to build a LWRsf separation facility, and the maximum percentage of FBRs that can be built each year. The reactor percentage of FBRs will range from 10%, 20% and ramp up to 100% of the energy growth per year in the simulation. Separation facility sizes will range from 1 Kt/yr, 0.5 Kt/yr and 0.25 Kt/yr. Note that the size of the facility is Kt of Heavy Metal per year, but the graphs are in Kt of TRU per year. Lead time for facilities will be analyzed at 7, 5, 4, 3 and 1 years. The lead time is the number of years that a facility will operate before separated material is requested by fuel fabrication, which is 3 years prior to fuel being placed in the reactor. The actual bank limit, shown in the inventory graphs, is set to a 1 year fuel supply for every operating FBR. This limit will be consistent throughout all of the results. The results will show how these three factors affect the build rate of separation facilities (or separation capacity) and the inventories that they accumulate during their operation. The overall trend in the optimum scenario will have the smoothest build rate of separations capacity and an inventory that remains close to the bank limit.

3.2.1 New FBR Build Held at 10% of Growth

In the following cases the FBR ordering will be limited to 10% of the energy growth that will be met by nuclear power. The separation facility size and the lead time for when a separations facility should come online will be varied.

The graph in Figure 3-5 shows the number of operating reactors and each type of reactor throughout the century. Figure 3-6 shows the deployed reactor capacity in GWe for each reactor type throughout the century. The deployed reactor capacity is the variable that is controlled in this simulation by limiting the FBR growth to 10% of the total growth in this figure. The number of reactors and their capacity will not change with a change in separations facility lead time or a change in the separations facility size.

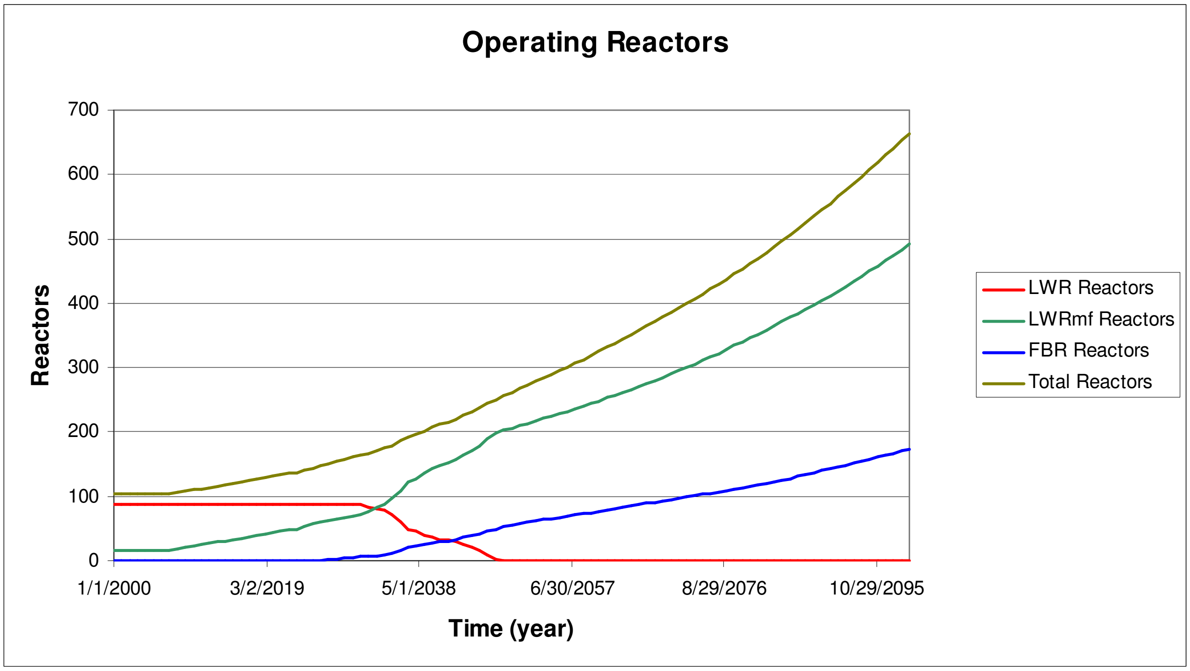

Figure 3-5: Number of Operating Reactors for Case 1

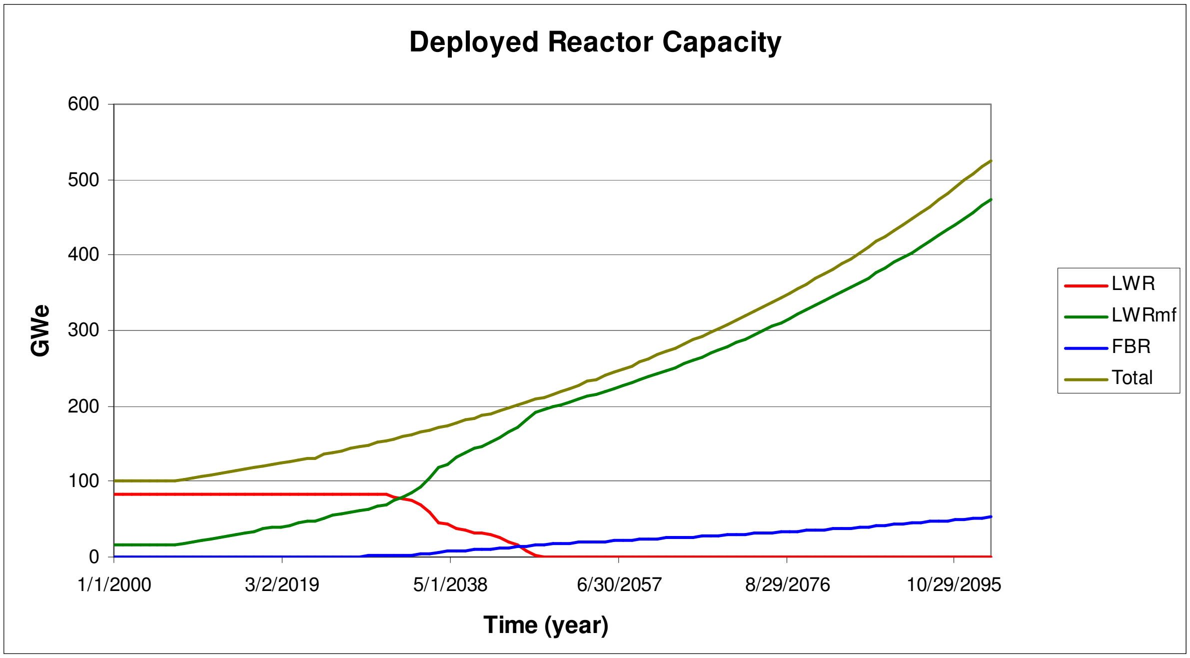

Figure 3-6: Deployed Reactor Capacity for Case 1

3.2.1.1 Case 1 Separation Facility Size of 1 Kt/yr

Summary of Case 1

The results of Case 1 show that a lead time of 5 years will result in the smoothest build schedule and smallest inventory. This happens because with a large lead time the inventory can build up to a reasonably sized level at the beginning in order to delay the addition of new separations capacity (Figure 3-11 and Figure 3-13). As the lead time decreases below 5 years the initial inventory shrinks and additional separation facilities come online earlier (Figure 3-23 and Figure 3-25). This causes facilities to come online in too short of a time to build up an inventory, which then causes the system to overbuild early on in the simulation.

Lead Time of 7 Years

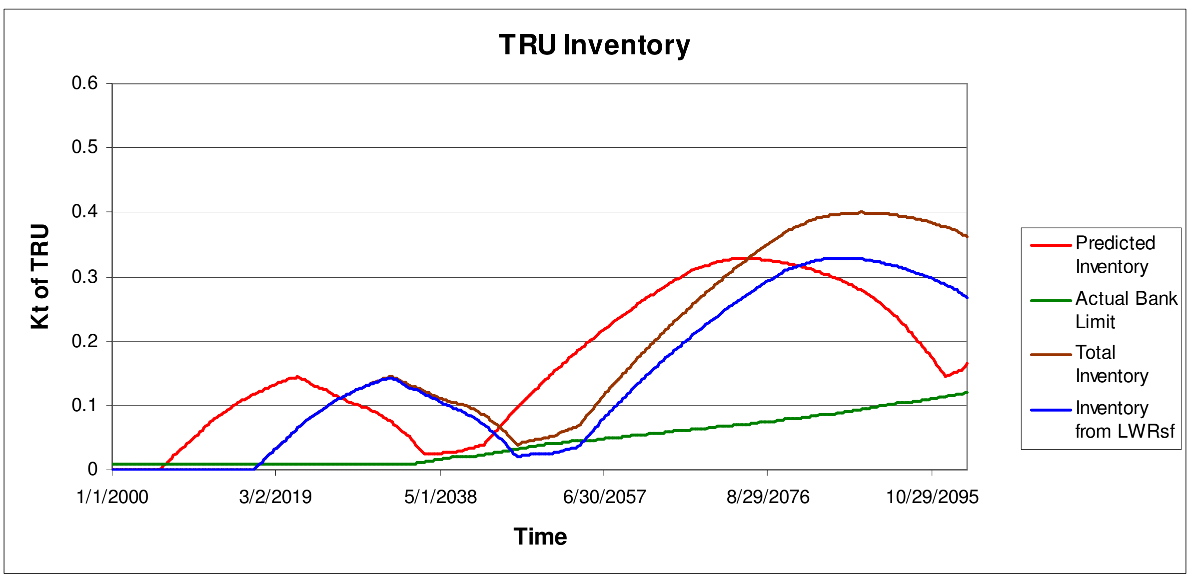

Figure 3-7: Case 1 TRU Inventory with 7 Year Lead Time

Figure 3-7 shows the TRU Inventory in the model and in the prediction with a separation facility lead time of 7 years. The red line is the predicted TRU inventory from aqueous separations, which is used by the simulation to determine when to build separation facilities. The predicted inventory is calculated with enough time to allow the system to license and build a new separation facility, if the predicted inventory drops below predicted minimum TRU bank limit. The blue line is the actual TRU inventory from aqueous separations in the model and should be equal to the predicted TRU inventory with a time shift. The green line is the TRU bank limit. This value has a minimum value of 0.01 Kt of TRU or one year TRU supply for every operating FBR. The brown line is the total TRU inventory. This value also includes TRU from fast separations, because the model lumps all of the separated material into one stock that is categorized by each pass that the fuel is in.

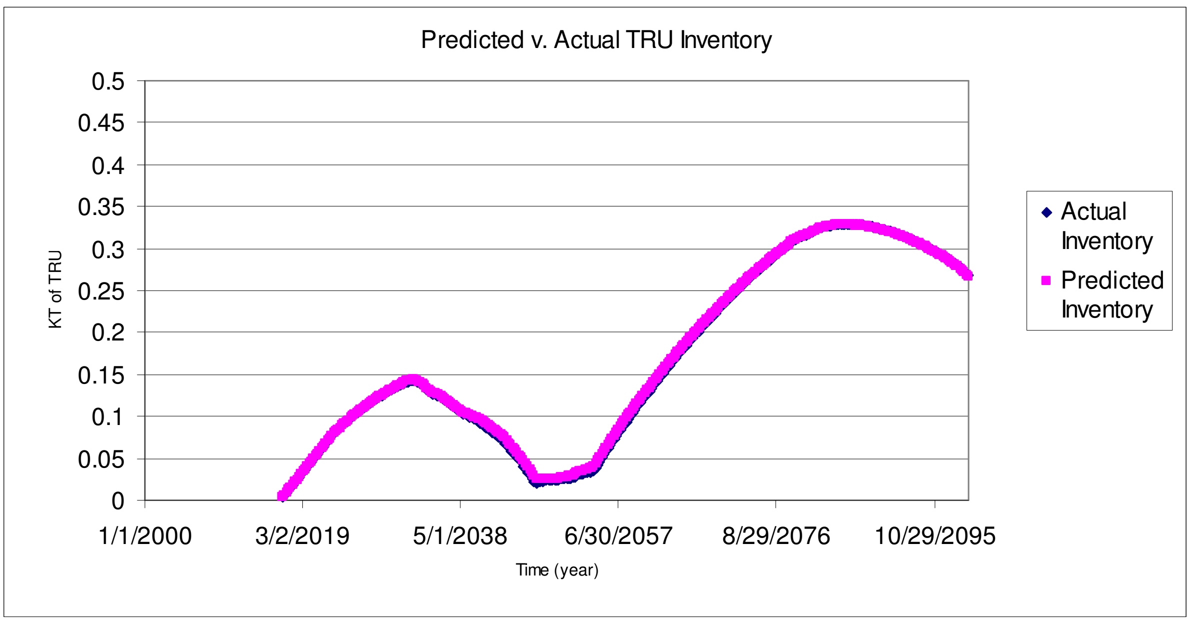

Figure 3-8: Case 1 Predicted v. Actual TRU Inventory with 7 Year Lead Time

The Predicted and Actual TRU Inventory in Figure 3-8 are the same inventories that are shows in Figure 3-7, only the time shift has been removed. This graph shows the accuracy of the predicted aqueous inventory.

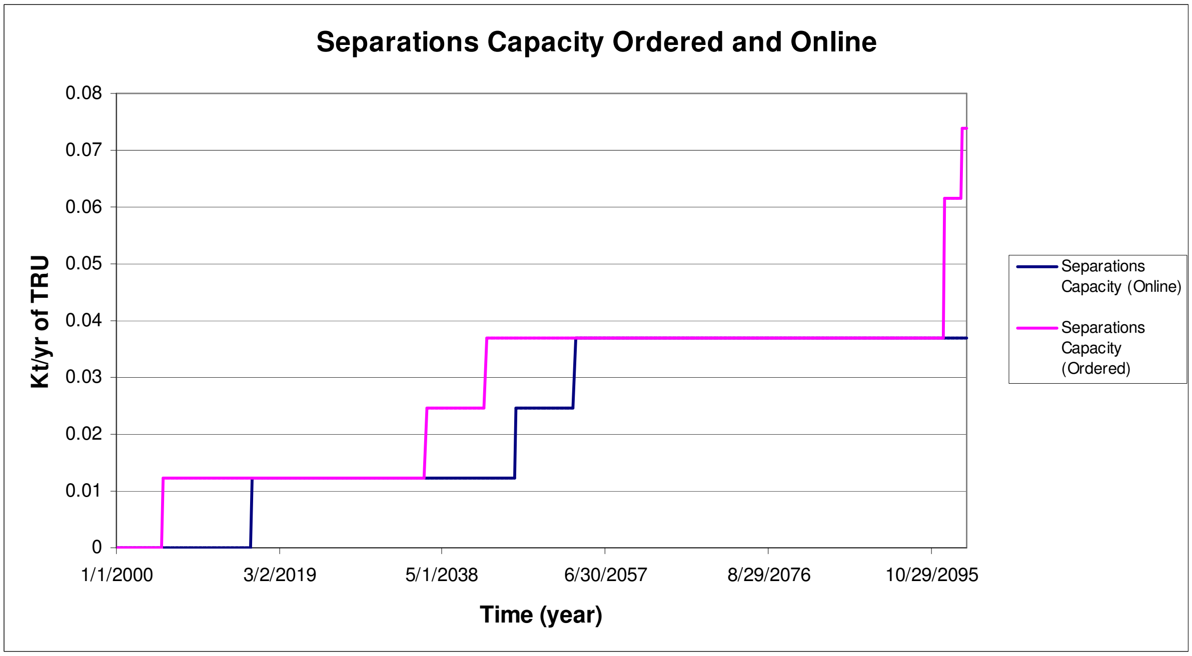

Figure 3-9: Case 1 Separations Capacity with a 7 Year Lead Time

The separations capacity shown in Figure 3-9 is a plot of the ordered and online separations capacity in Kt/yr of TRU. The pink line is the separations capacity that has been ordered and the blue line is the separations capacity that is online. Facilities are ordered depending on their license and construction time and their lead time (7 years). The separations capacity is directly proportional to the separations facilities ordered and online.

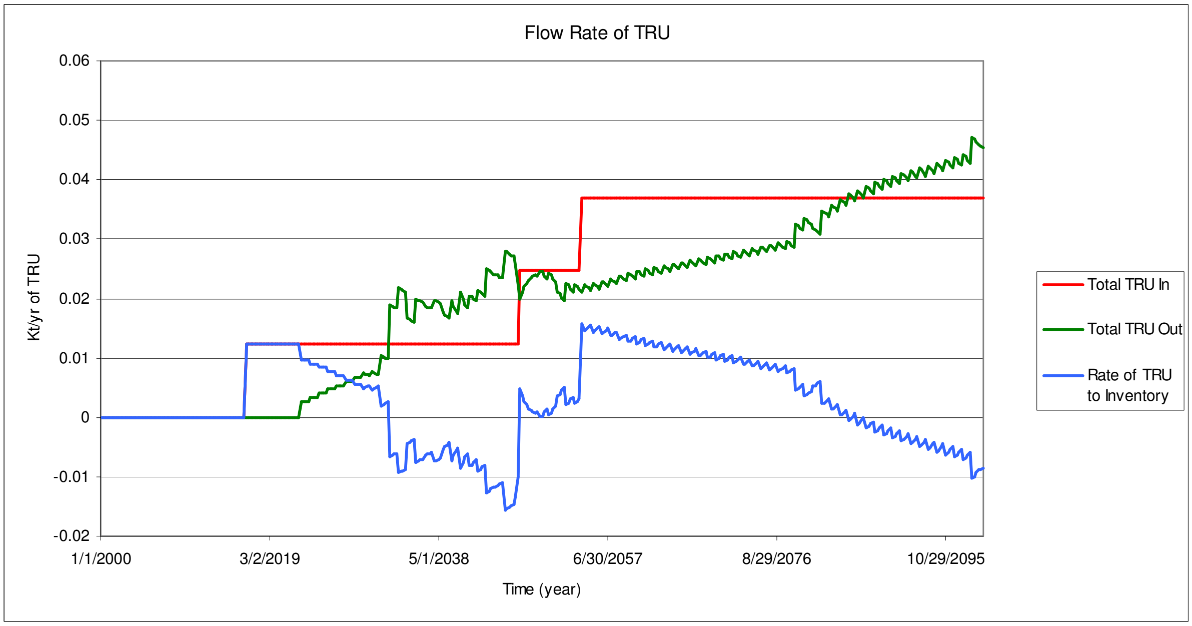

Figure 3-10: Case 1 Flow Rate of TRU to the Predicted Inventory with 7 Year Lead Time

The flow rate of TRU in Figure 3-10 shows the rate that TRU enters the predicted inventory and the rate that TRU flows out of the predicted inventory. The rate of TRU to Inventory (blue line) is simply the difference between the rate in and the rate out. This value will range from positive to negative depending on the separations capacity online and the number of FBRs requesting fuel.

In the next several pages Figure 3-11 - Figure 3-14, Figure 3-15 - Figure 3-18, Figure 3-19 - Figure 3-22, and Figure 3-23 - Figure 3-26 present the same results for a 5 year, 4 year, 3 year and 1 year lead time. These results will be used to determine the most optimum deployment scenario for separation facilities with the given growth rate and separation facility size.

<u>Lead Time of 5 Years</u>

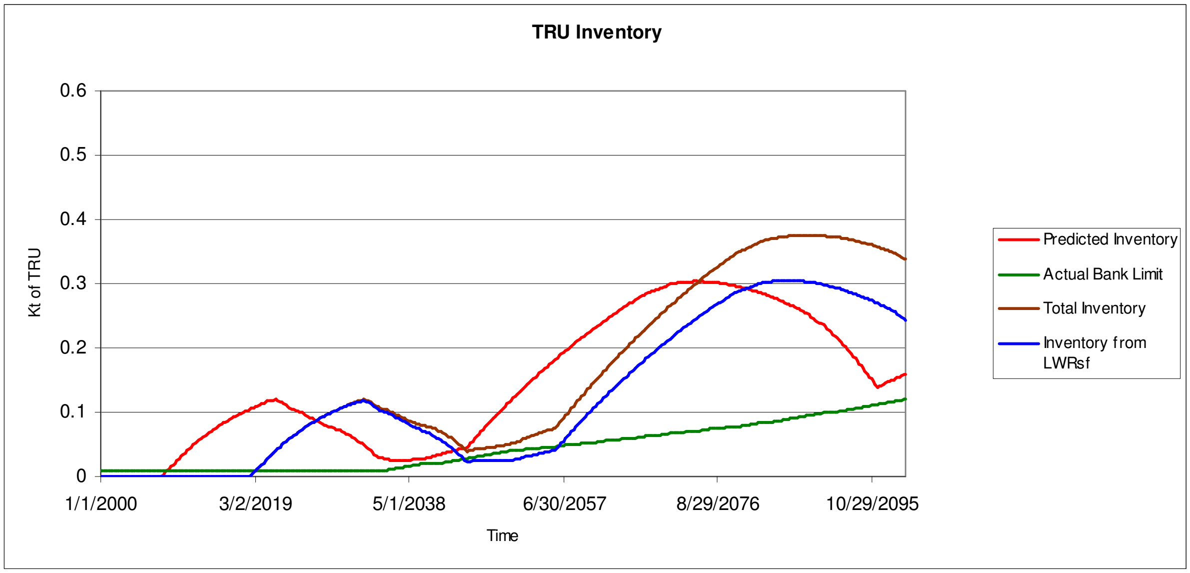

Figure 3-11: Case 1 TRU Inventory with a 5 Year Lead Time

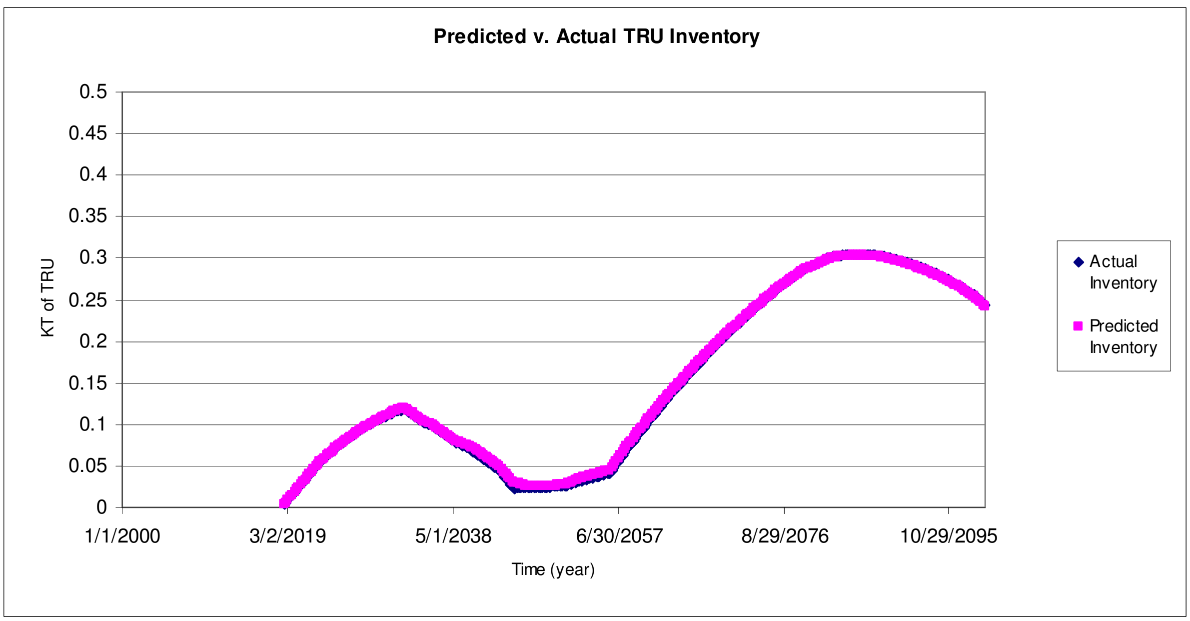

Figure 3-12: Case 1 Predicted v. Actual Inventory with a 5 Year Lead Time

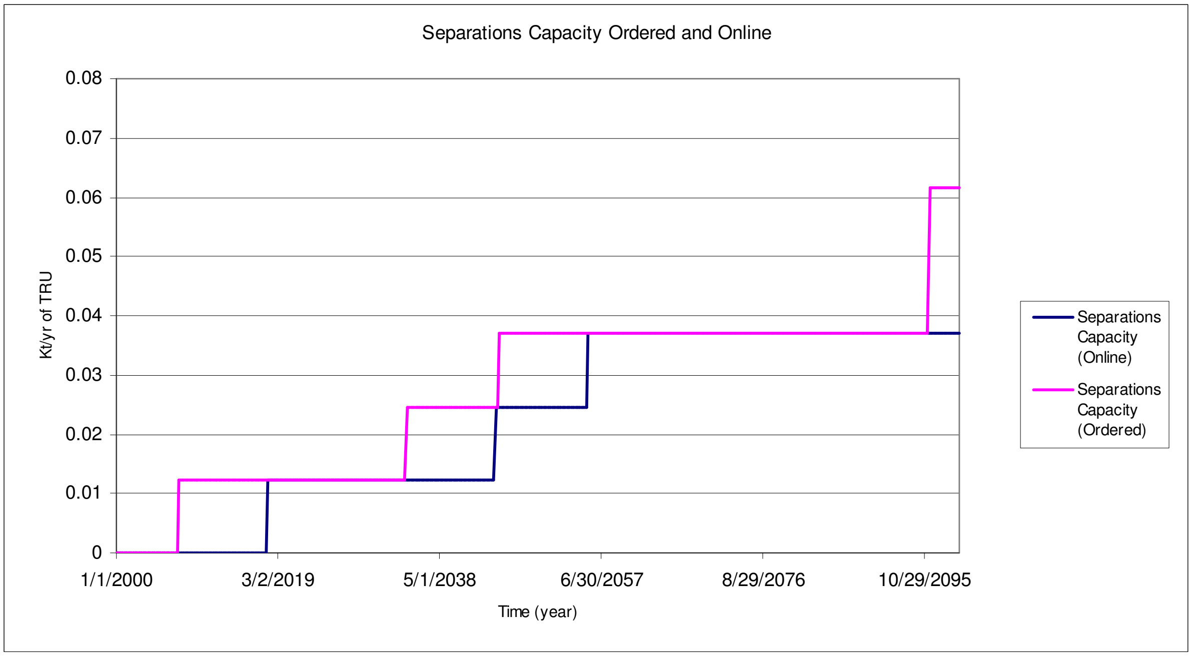

Figure 3-13: Case 1 Separations Capacity with a 5 Year Lead Time

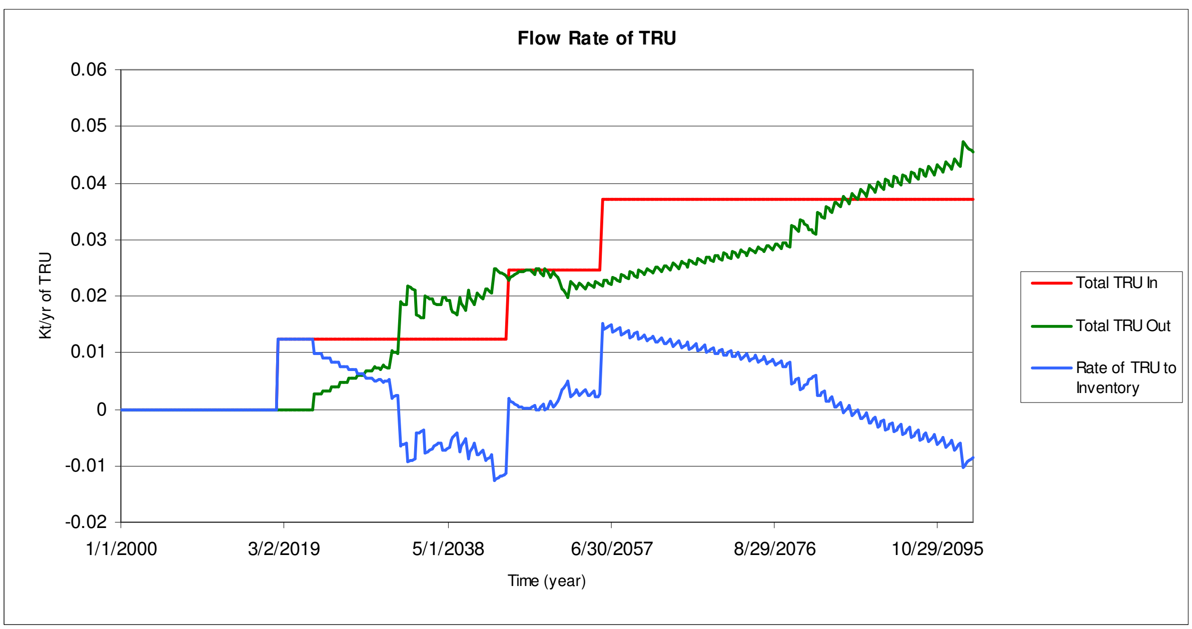

Figure 3-14: Case 1 Flow Rate of TRU to Predicted Inventory with a 5 Year Lead Time

Lead Time of 4 Years

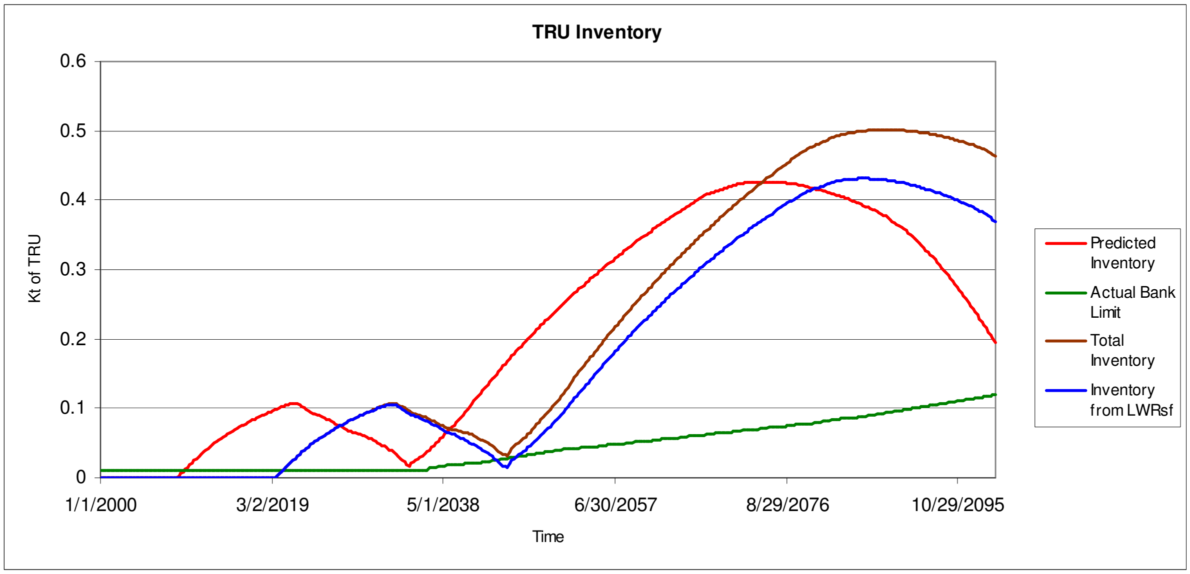

Figure 3-15: Case 1 TRU Inventory with a 4 Year Lead Time

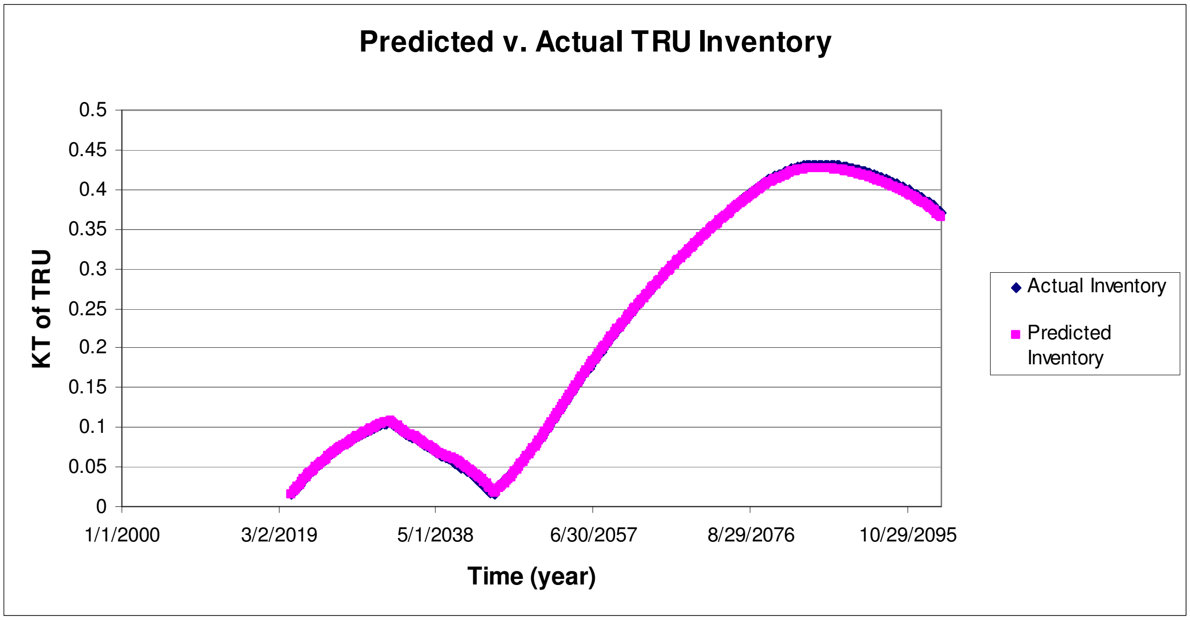

Figure 3-16: Case 1 Predicted v. Actual Inventory with a Lead Time of 4 Years

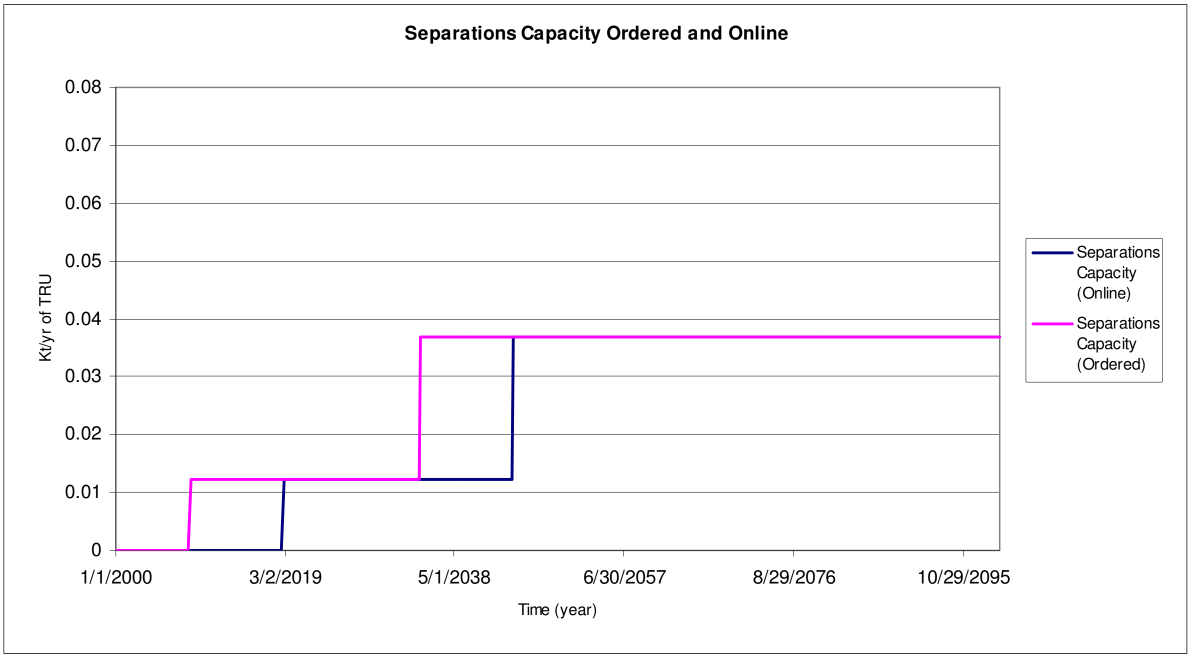

Figure 3-17: Case 1 Separations Capacity with a 4 Year Lead Time

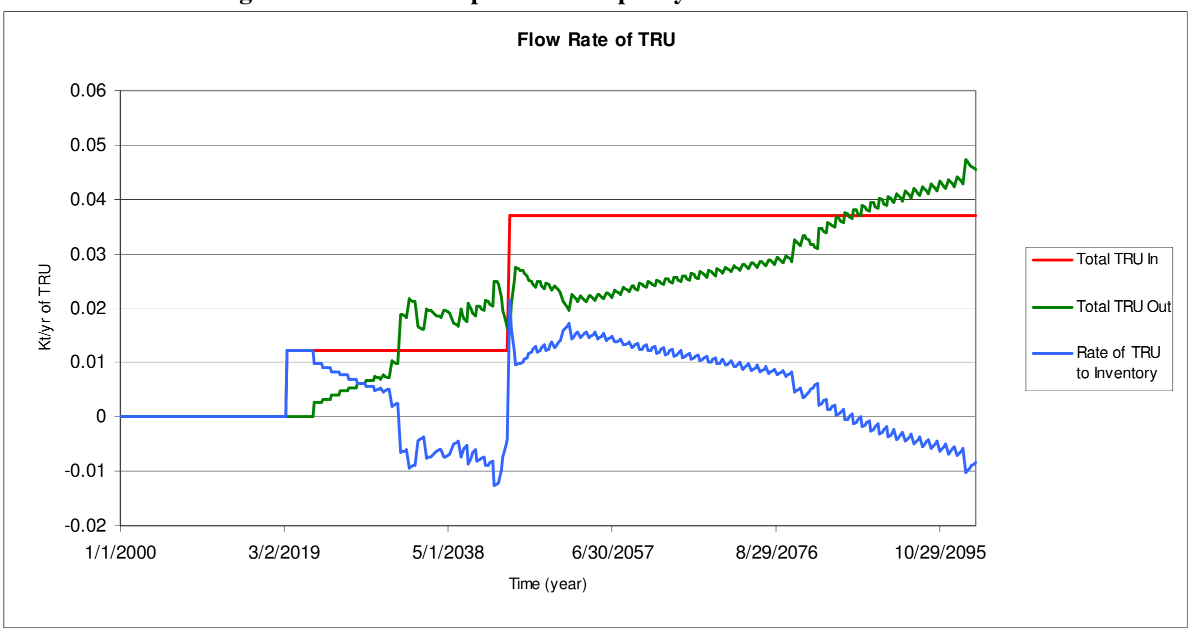

Figure 3-18: Case 1 Flow Rate of TRU to Predicted Inventory with a 4 Year Lead Time

Lead Time of 3 Years

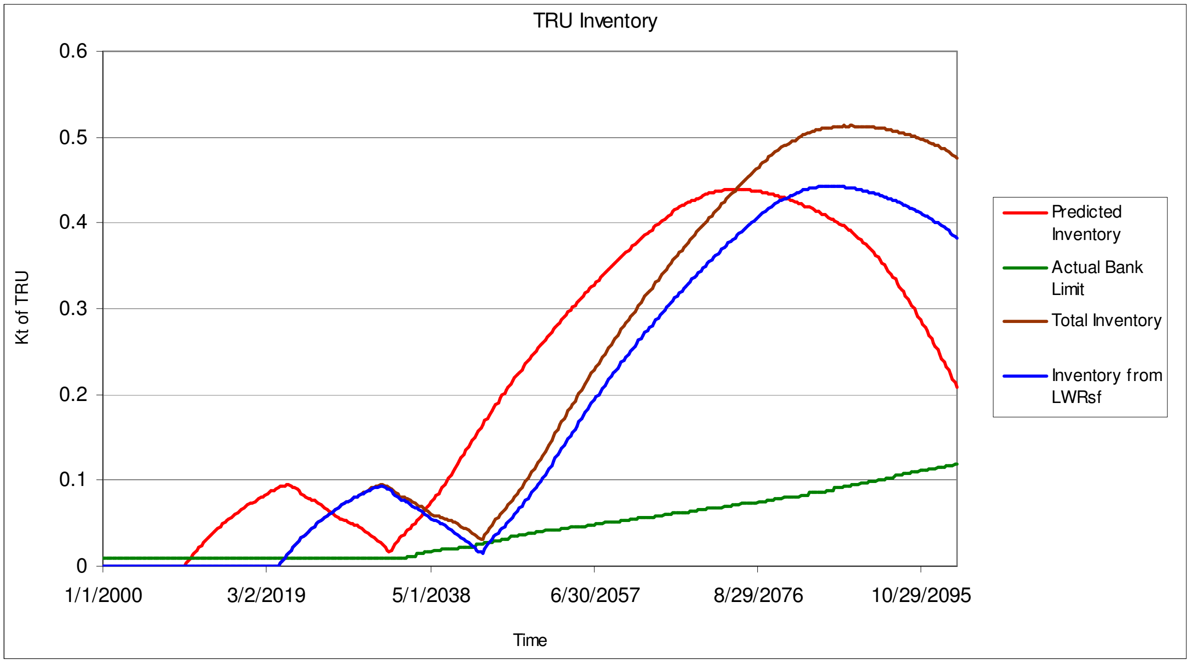

Figure 3-19: Case 1 TRU Inventory with a Lead Time of 3 Years

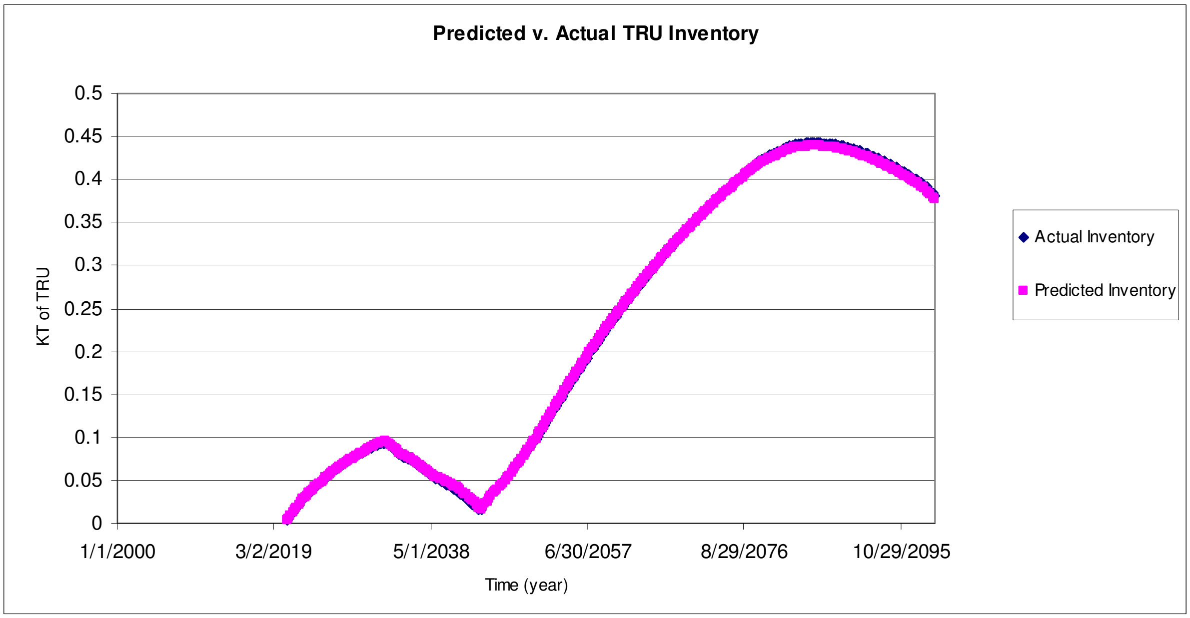

Figure 3-20: Case 1 Predicted v. Actual Inventory of TRU with a Lead time of 3 Years

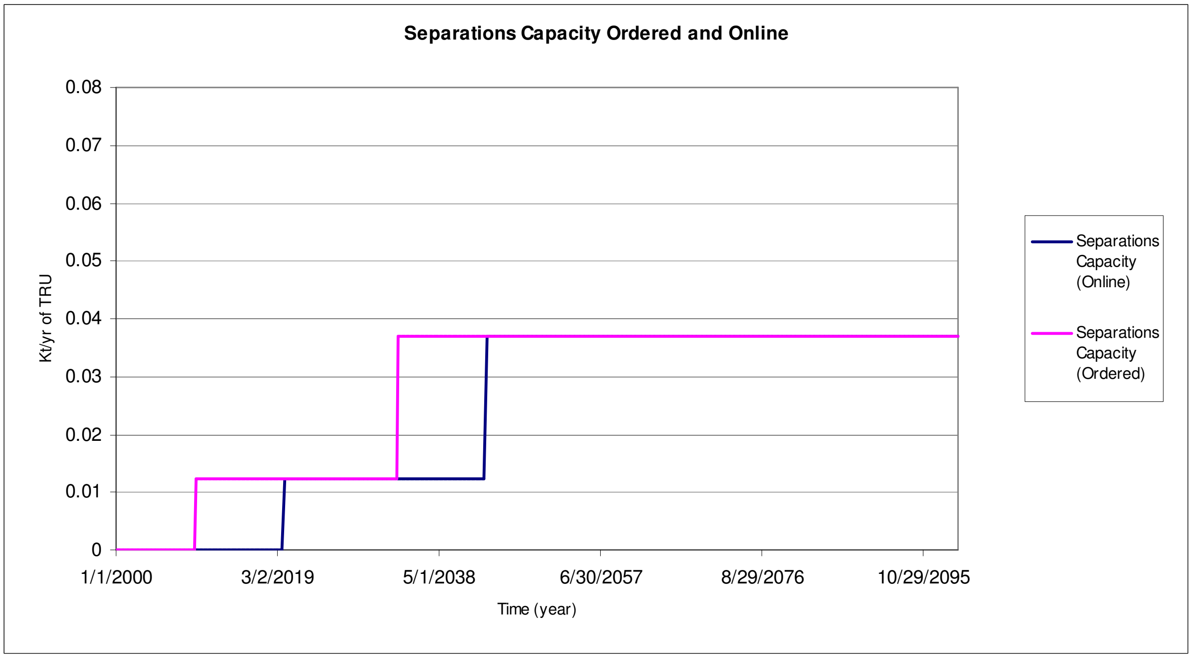

Figure 3-21: Case 1 Separation Capacity with a 3 Year Lead Time

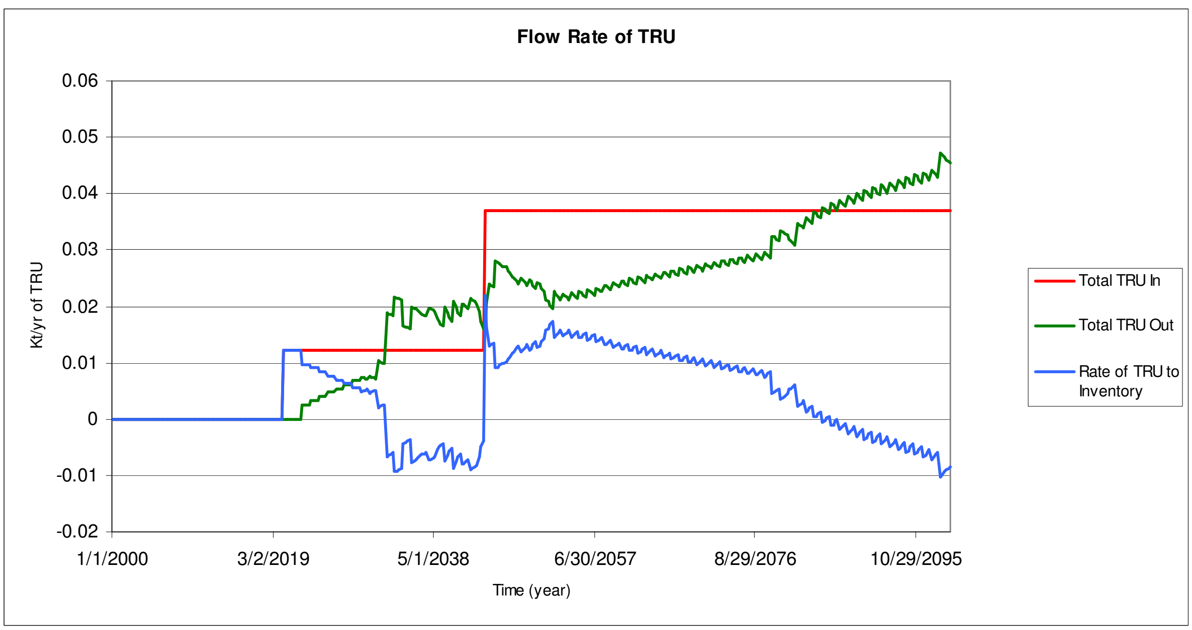

Figure 3-22: Case 1 TRU Flow Rate to Predicted Inventory with a Lead Time of 3 Years

Lead Time is 1 Year

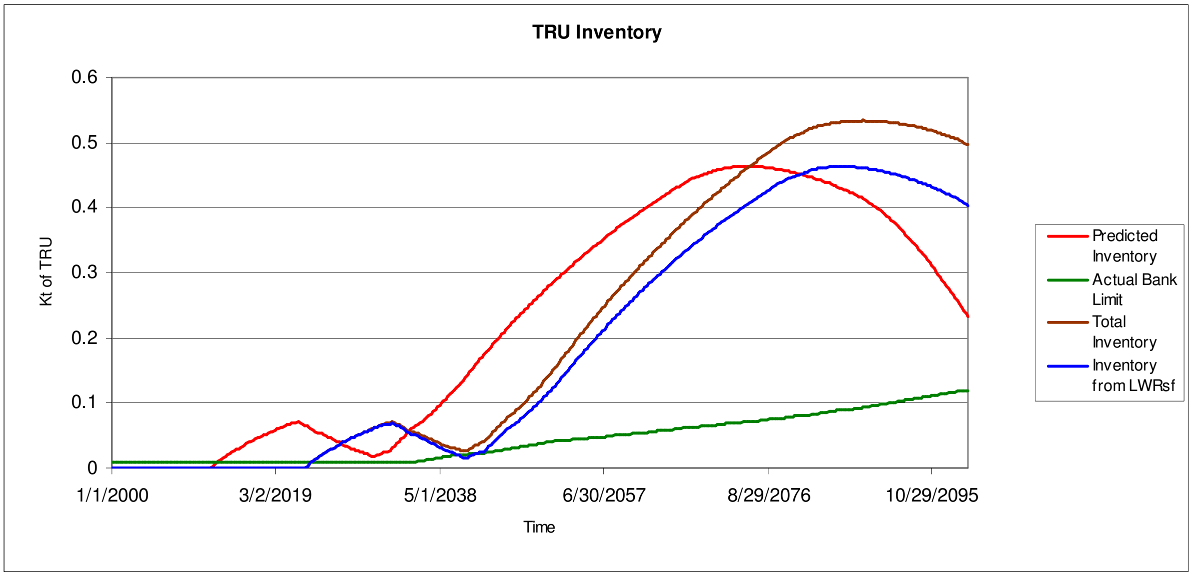

Figure 3-23: Case 1 TRU Inventory with a 1 Year Lead Time

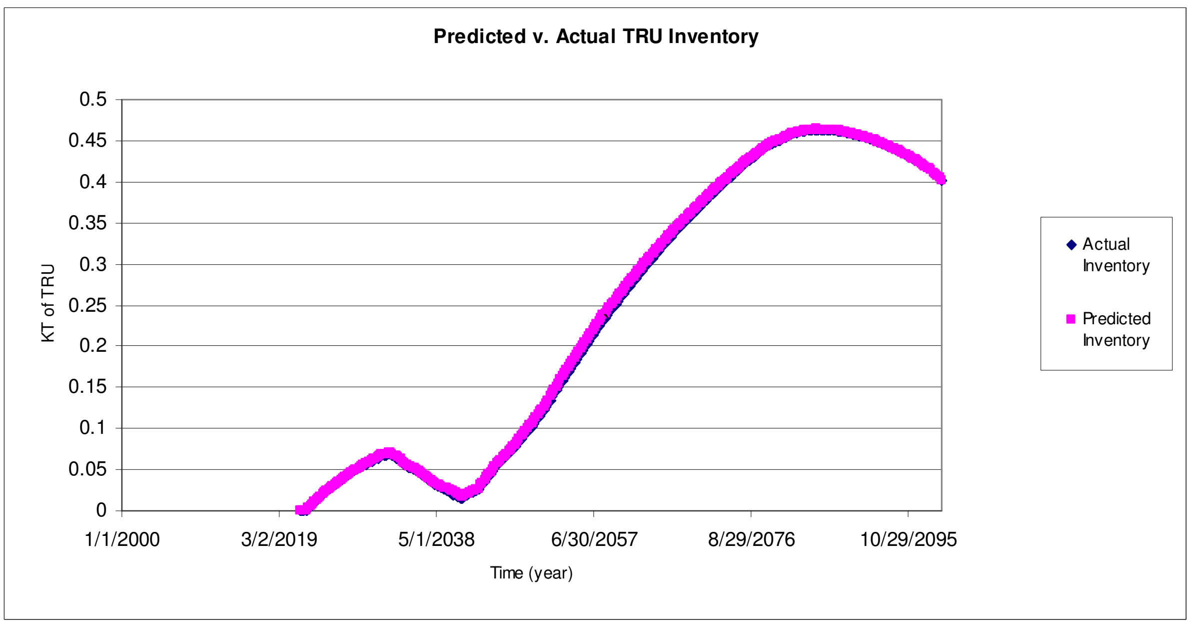

Figure 3-24: Case 1 Predicted v. Actual Inventory with a Lead Time of 1 Year

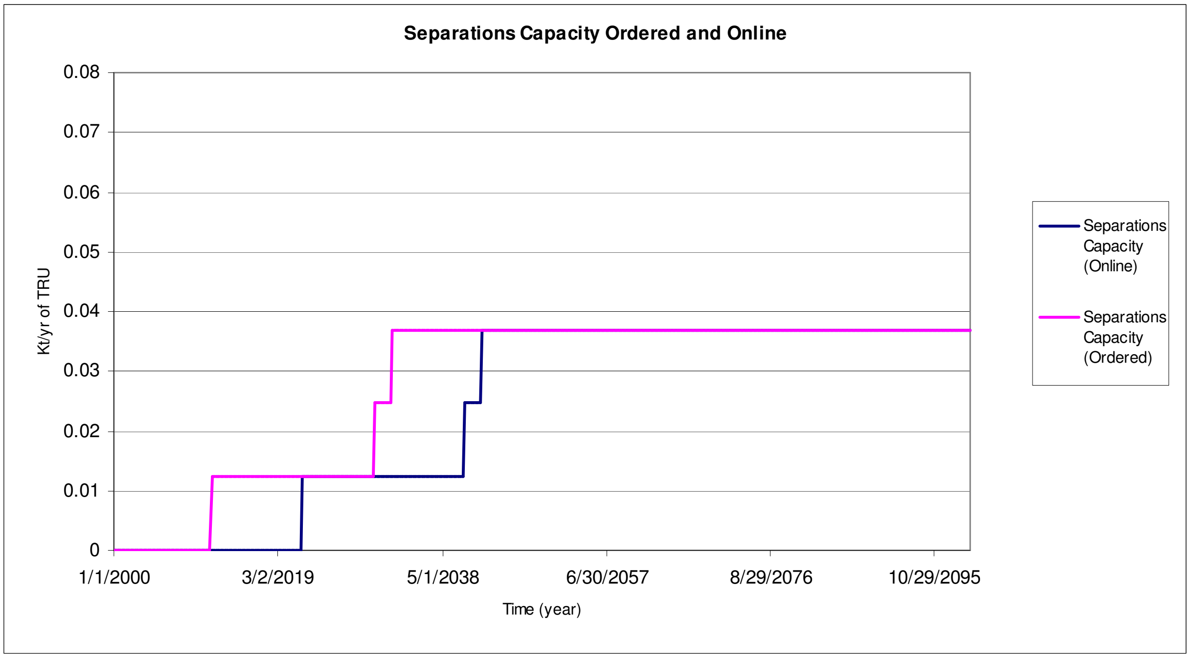

Figure 3-25: Case 1 Separations Capacity with a 1 Year Lead Time

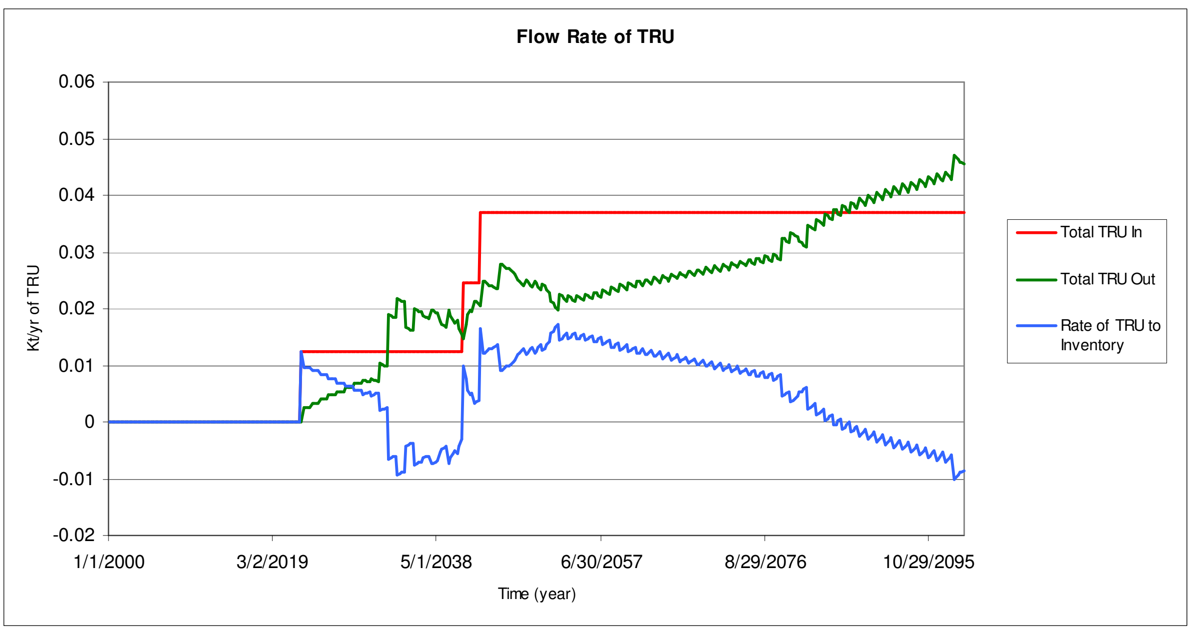

Figure 3-26: Case 1 TRU Flow Rate to Predicted Inventory with a 1 Year Lead Time

3.2.1.2 Case 2 Separation Facility Size of 0.5 Kt/yr

Summary of Case 2

The most efficient build scenario for a growth rate of 10% FBRs and a separations facility size of 0.5 Kt/yr has a lead time of 1 year. This is seen by analyzing the following results. With a large lead time (7 and 5 years) too many facilities are built too soon. This can be seen by comparing the separation capacities of Figure 3-29 and Figure 3-33 with that of Figure 3-45. In Figure 3-29 and Figure 3-33 too many facilities are ordered because the lead time is so large. This causes their inventories to be too large later on in the simulation (Figure 3-27 and Figure 3-31). The inventories of the 4 and 3 year lead times (Figure 3-35 and Figure 3-39 respectively) are very similar to the inventory with the 1 year lead time (Figure 3-43); however, the 1 year lead time has the lowest inventory at the end of the century and the smoothest build rate of separations capacity (Figure 3-45).

The number of operating reactors and the deployed reactor capacity for Case 2 are the same as those for Case 1 (shown in Figure 3-5 and Figure 3-6); therefore, these figures will not need to be shown unless a new FBR % growth is used in the simulation. The data presented in Figure 3-27 - Figure 3-30, Figure 3-31 - Figure 3-34, Figure 3-35 - Figure 3-38, Figure 3-39 - Figure 3-42, and Figure 3-43 - Figure 3-46 represent the results for lead times of 7 years, 5 years, 4 years, 3 years and 1 year, respectively.

Lead Time of 7 Years

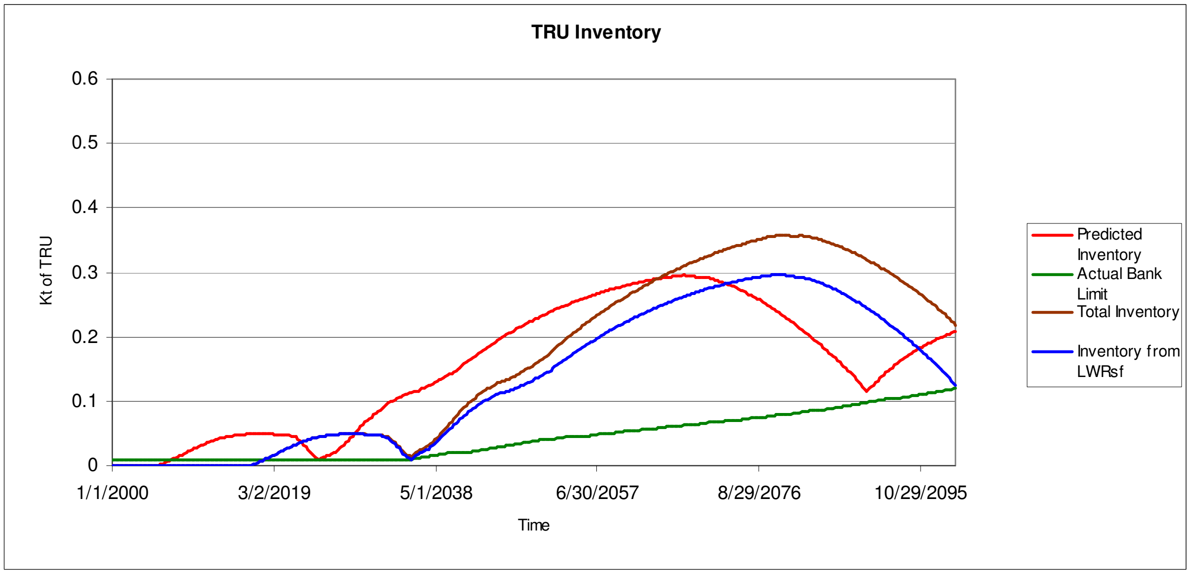

Figure 3-27: Case 2 TRU Inventory with a 7 Year Lead Time

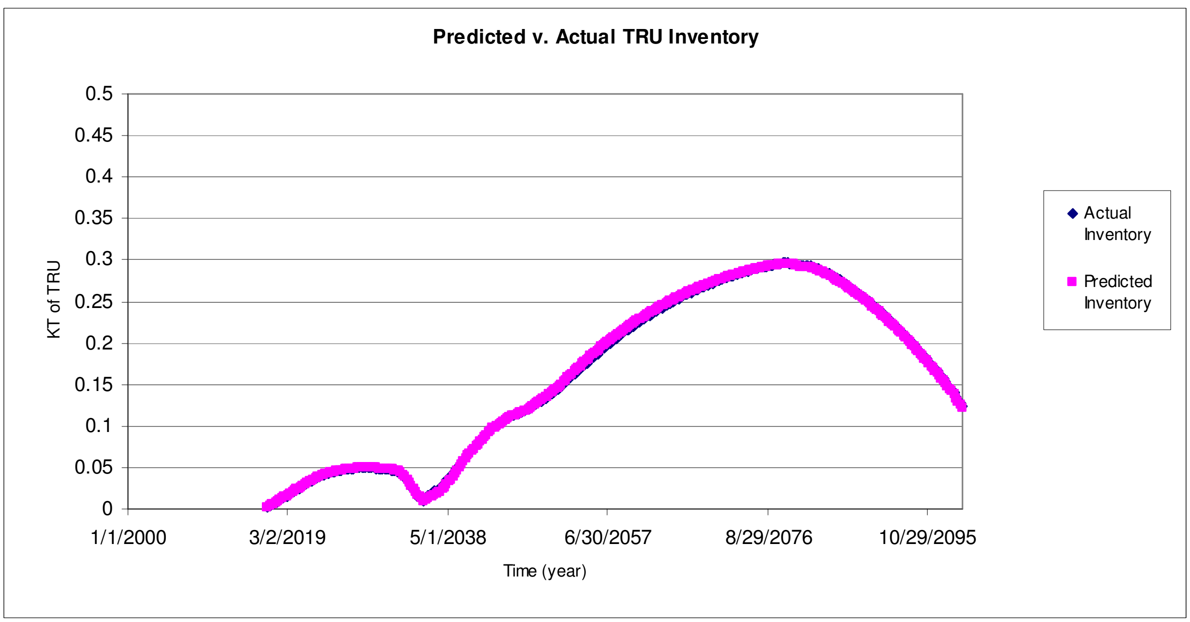

Figure 3-28: Case 2 Predicted v. Actual Inventory with a 7 Year Lead Time

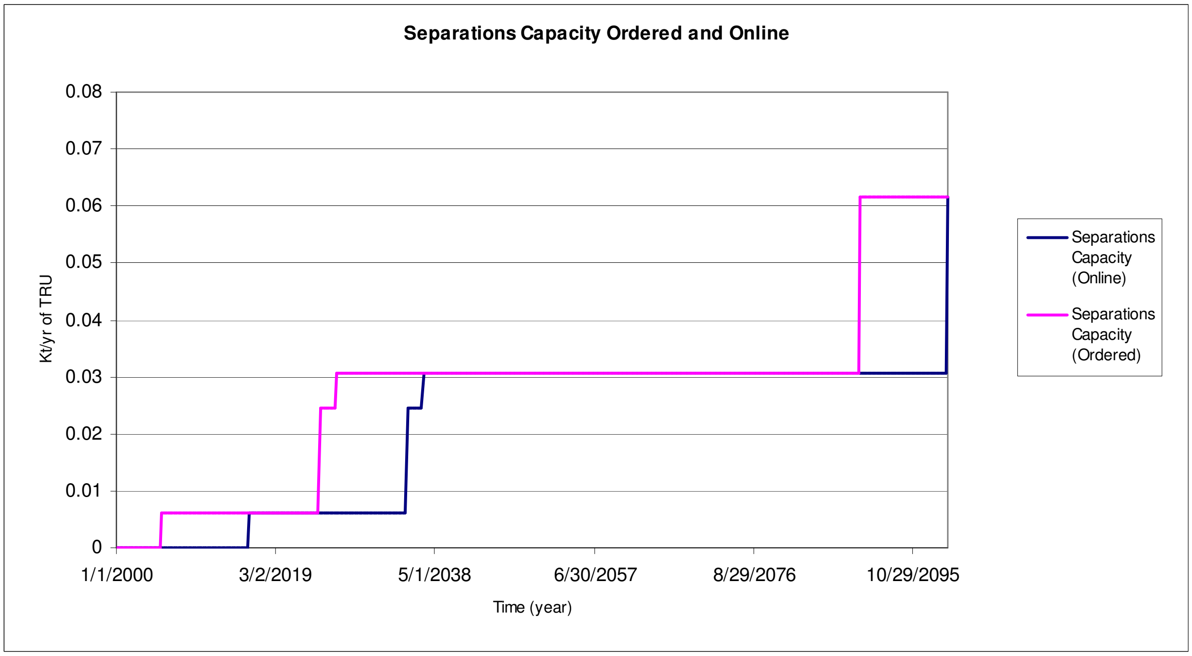

Figure 3-29: Case 2 Separations Capacity with a 7 Year Lead Time

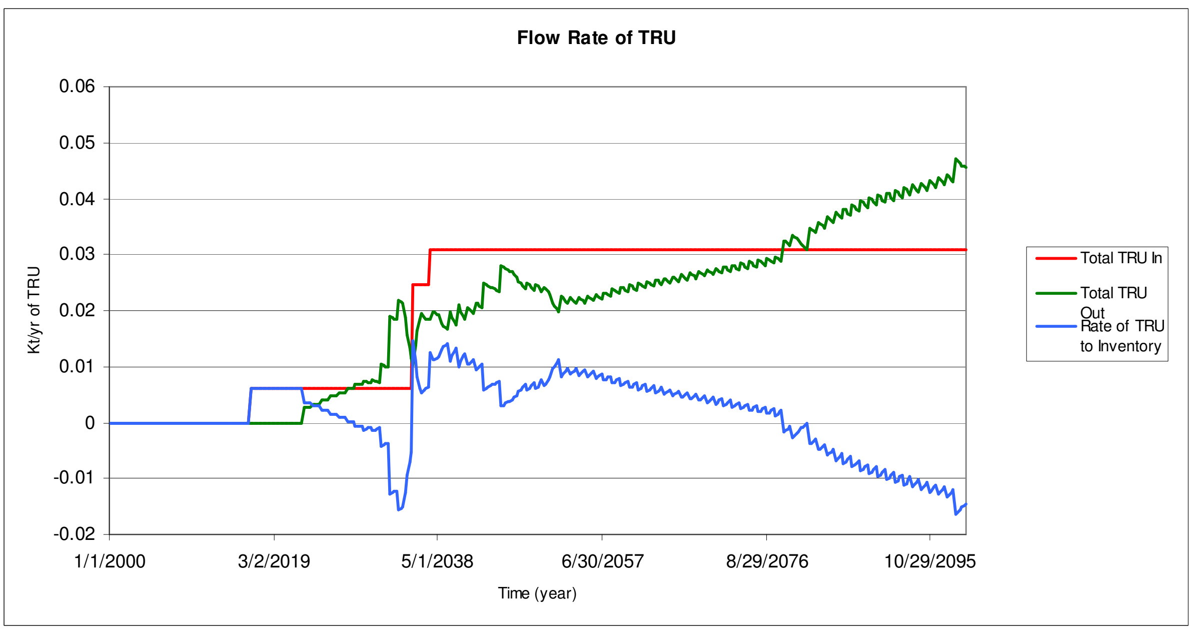

Figure 3-30: Case 2 TRU Flow Rate to Predicted Inventory with 7 Year Lead Time

Lead Time of 5 Years

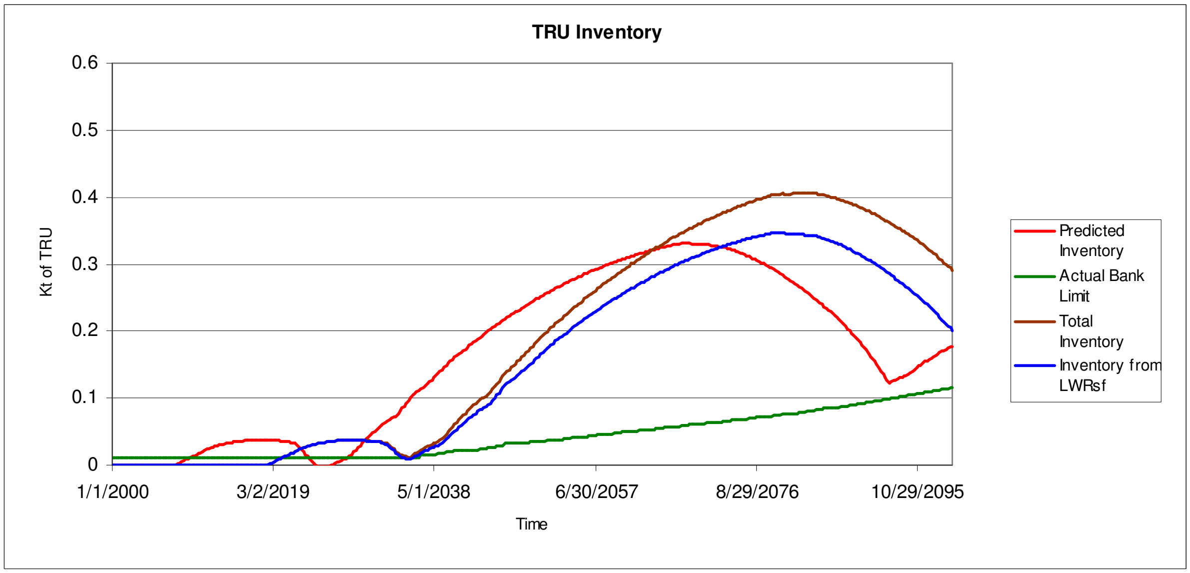

Figure 3-31: Case 2 TRU Inventory with a 5 Year Lead Time

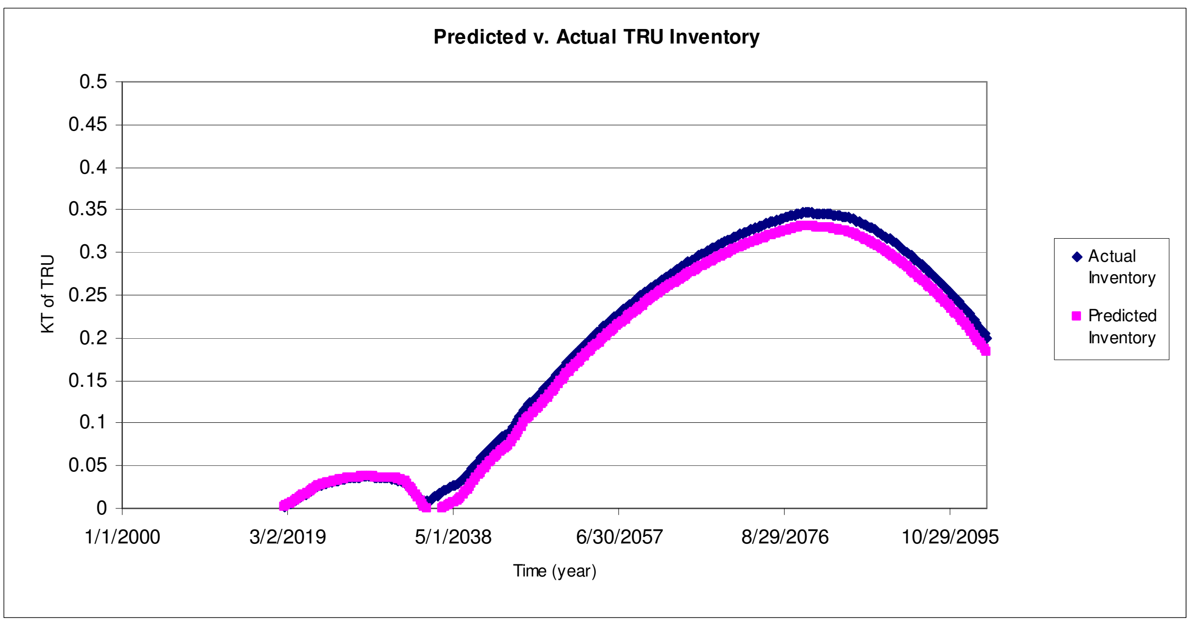

Figure 3-32: Case 2 Predicted v. Actual Inventory with a 5 Year Lead Time

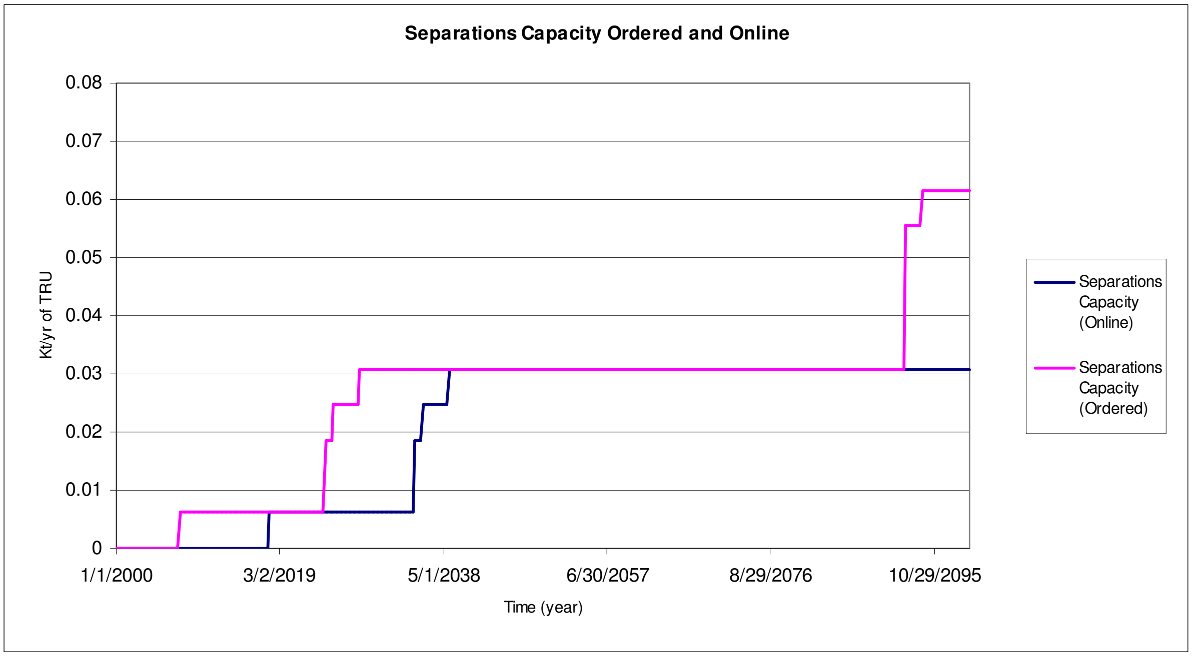

Figure 3-33: Case 2 Separations Capacity with a 5 Year Lead Time

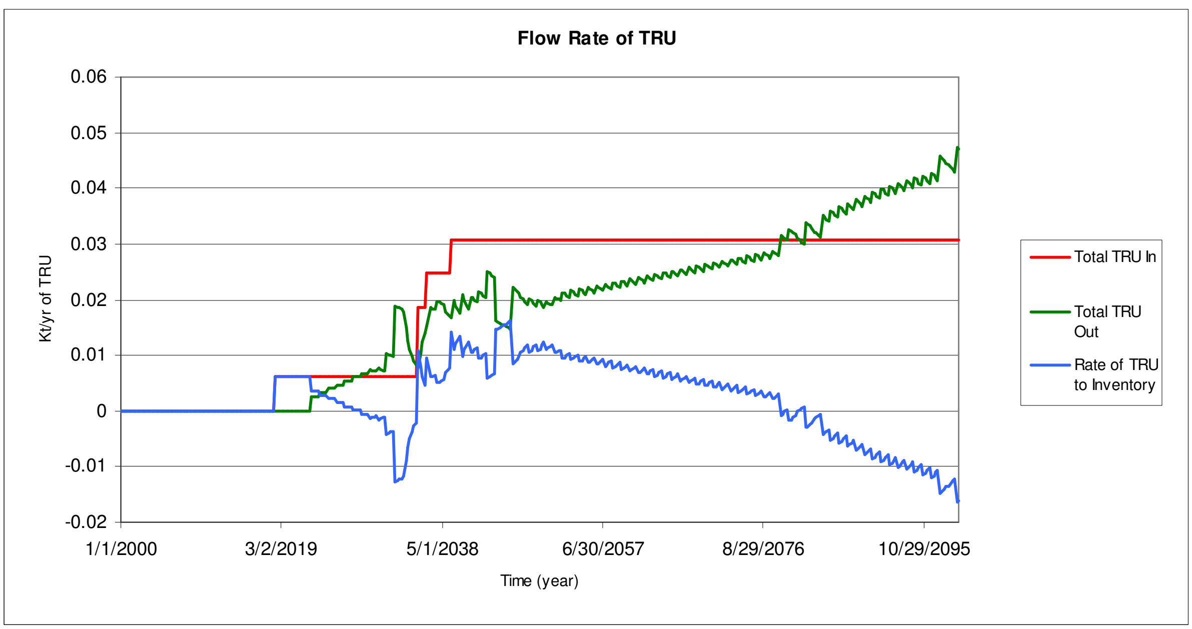

Figure 3-34: Case 2 TRU Flow Rate to Predicted Inventory with a 5 Year Lead Time

Lead time of 4 Years

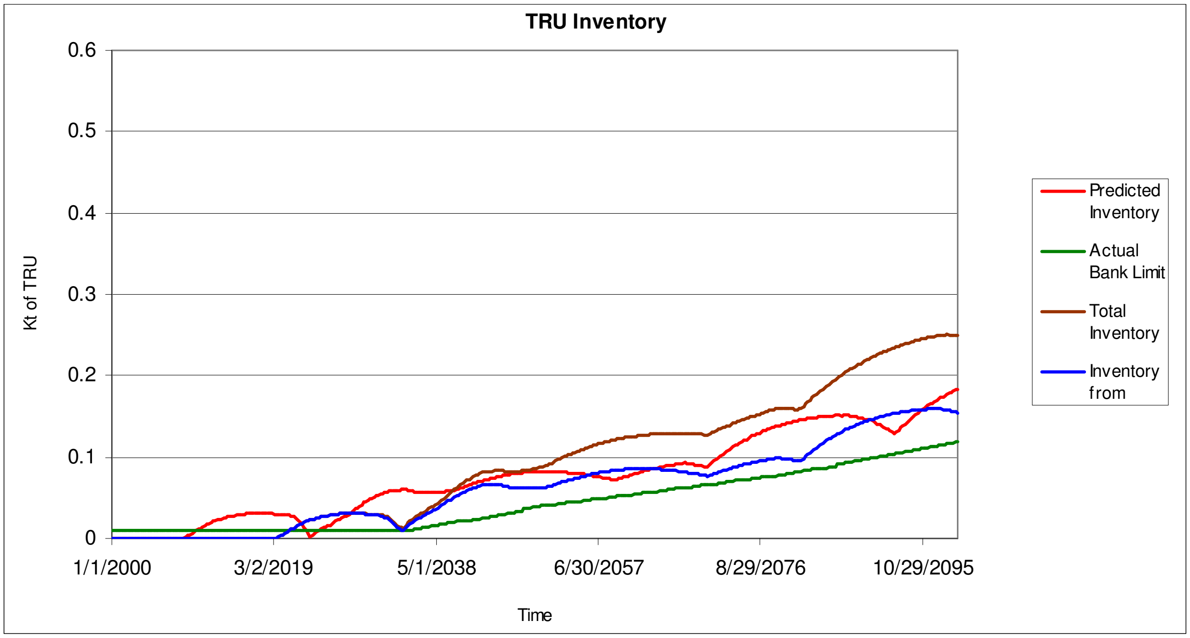

Figure 3-35: Case 2 TRU Inventory with a 4 Year Lead Time

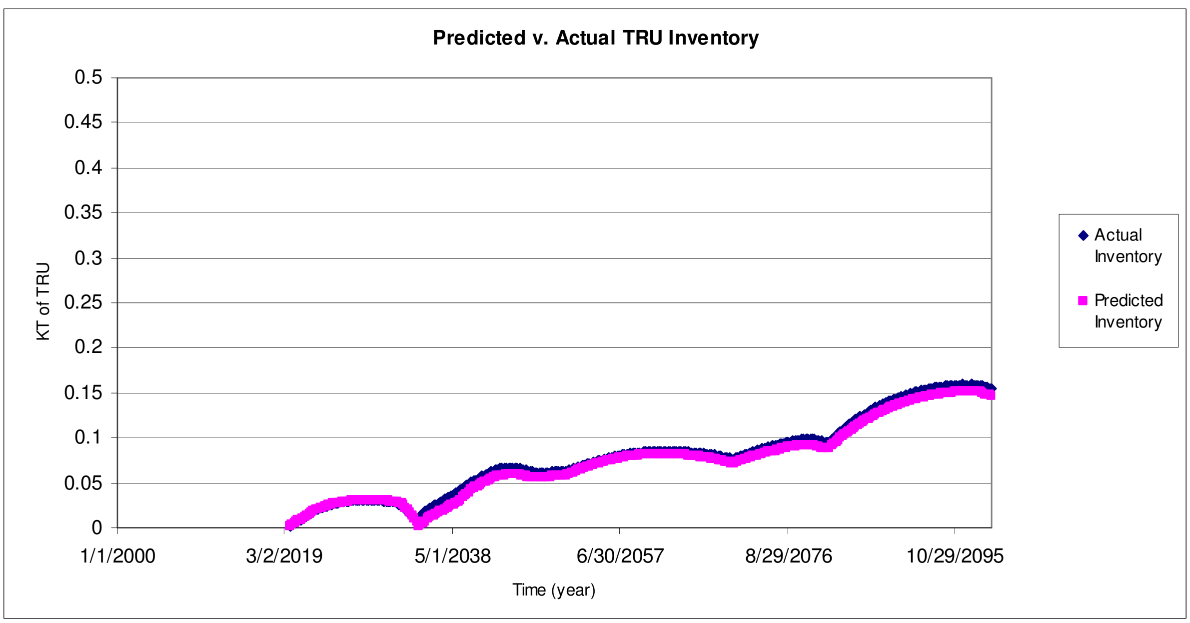

Figure 3-36: Case 2 Predicted v. Actual Inventory with a 4 Year Lead Time

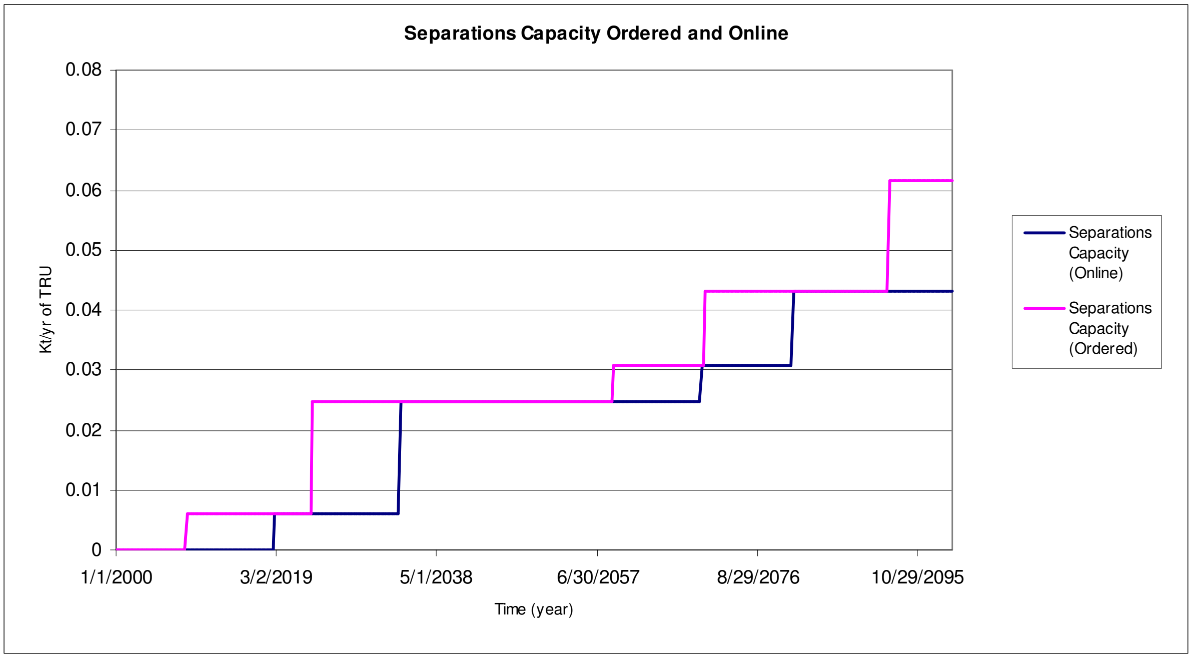

Figure 3-37: Case 2 Separations Capacity with a 4 Year Lead Time

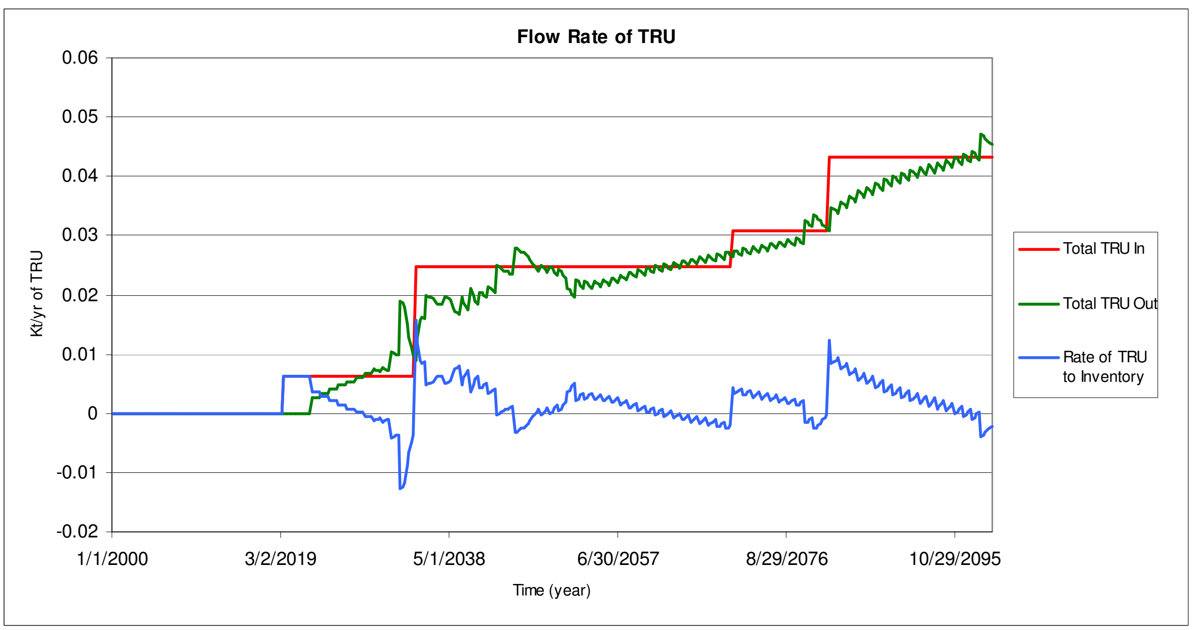

Figure 3-38: Case 2 Flow Rate of TRU to Predicted Inventory with a 4 Year Lead Time

Lead Time of 3 Years

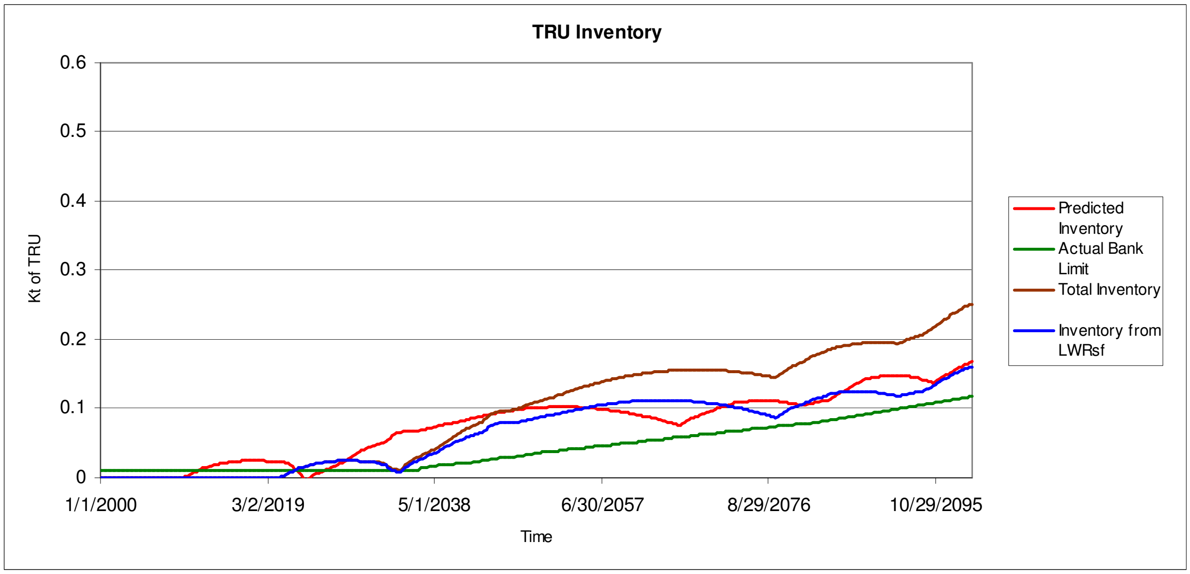

Figure 3-39: Case 2 TRU Inventory with a 3 Year Lead Time

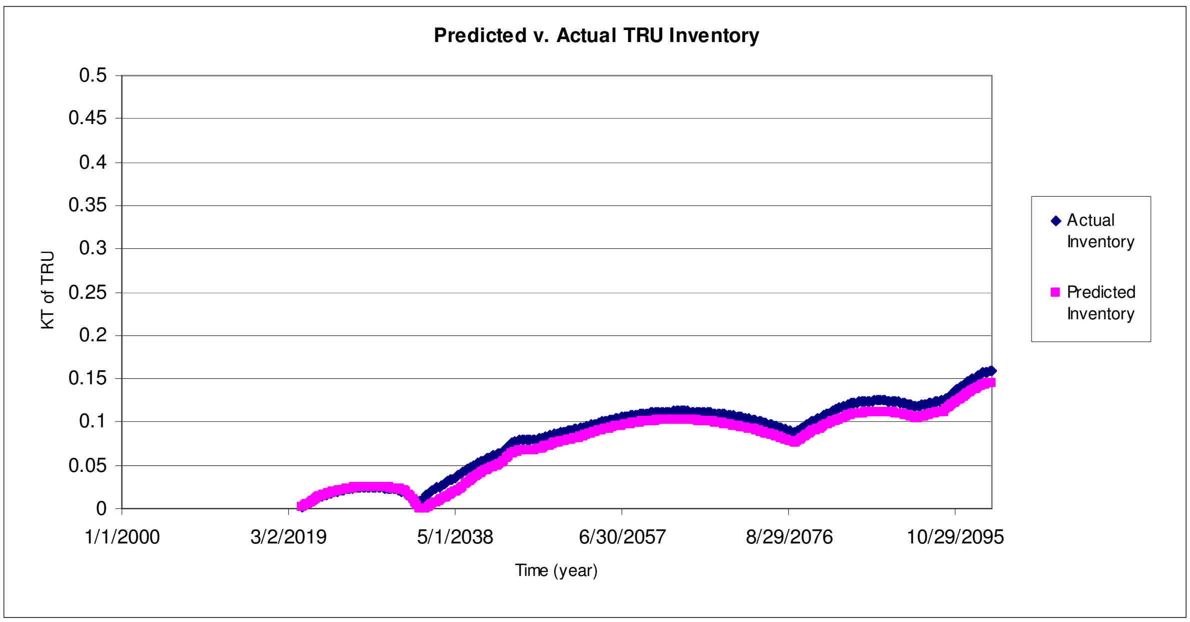

Figure 3-40: Case 2 Predicted v. Actual Inventory with a 3 Year Lead Time

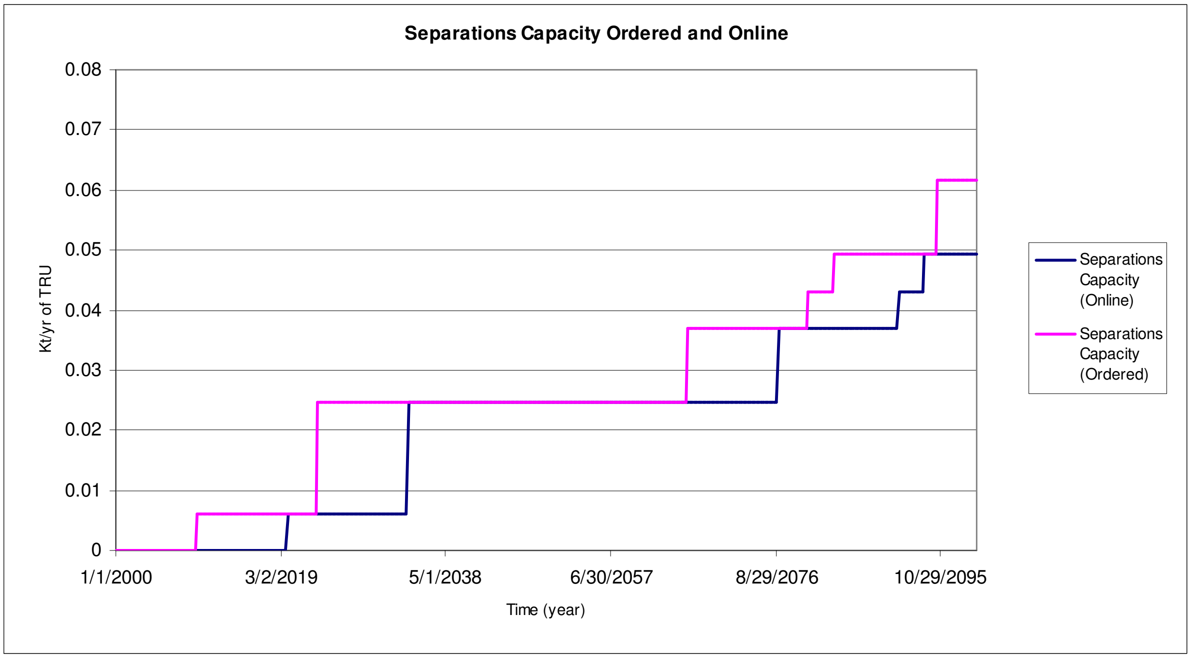

Figure 3-41: Case 2 Separations Capacity with a 3 Year Lead Time

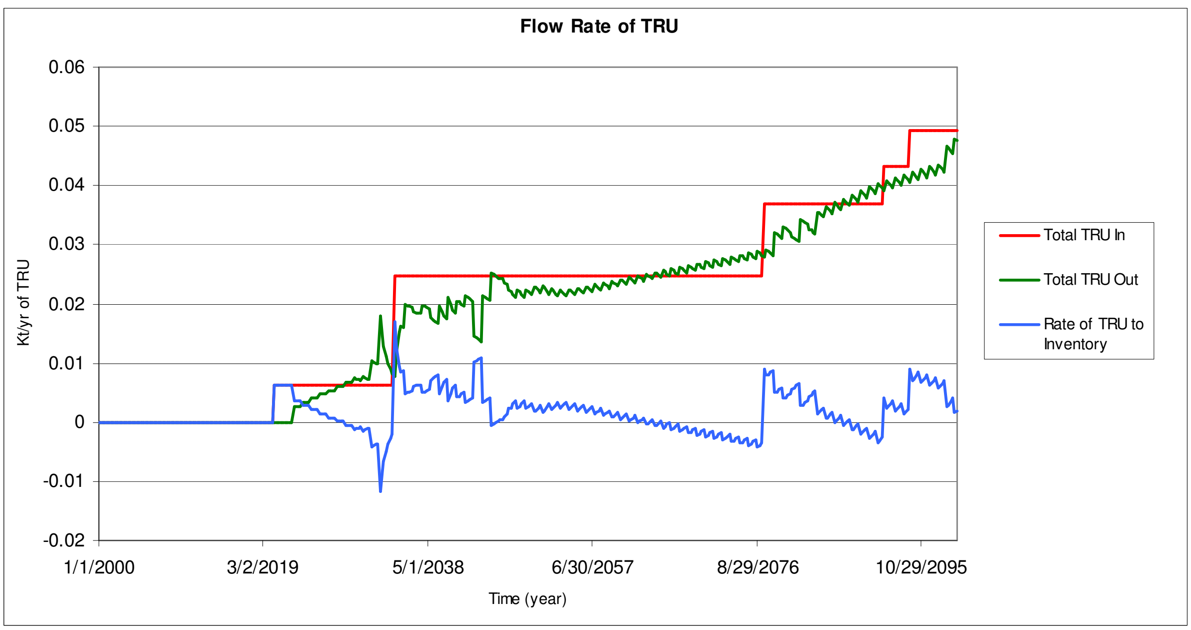

Figure 3-42: Case 2 Flow Rate of TRU to Predicted Inventory with a 3 Year Lead Time

Lead Time of 1 Year

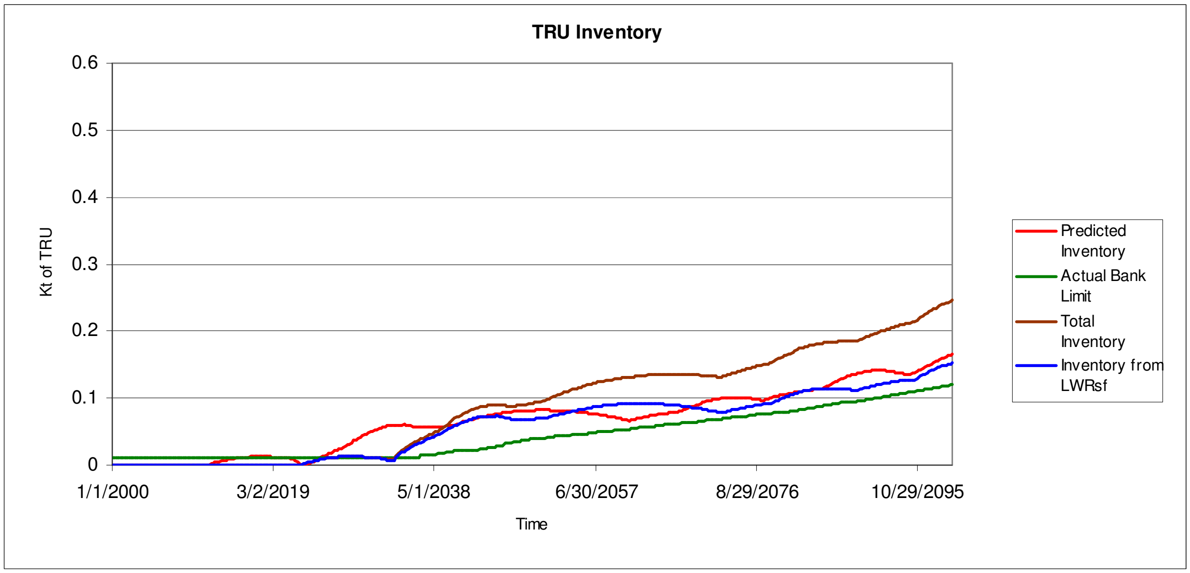

Figure 3-43: Case 2 TRU Inventory with a 1 Year Lead Time

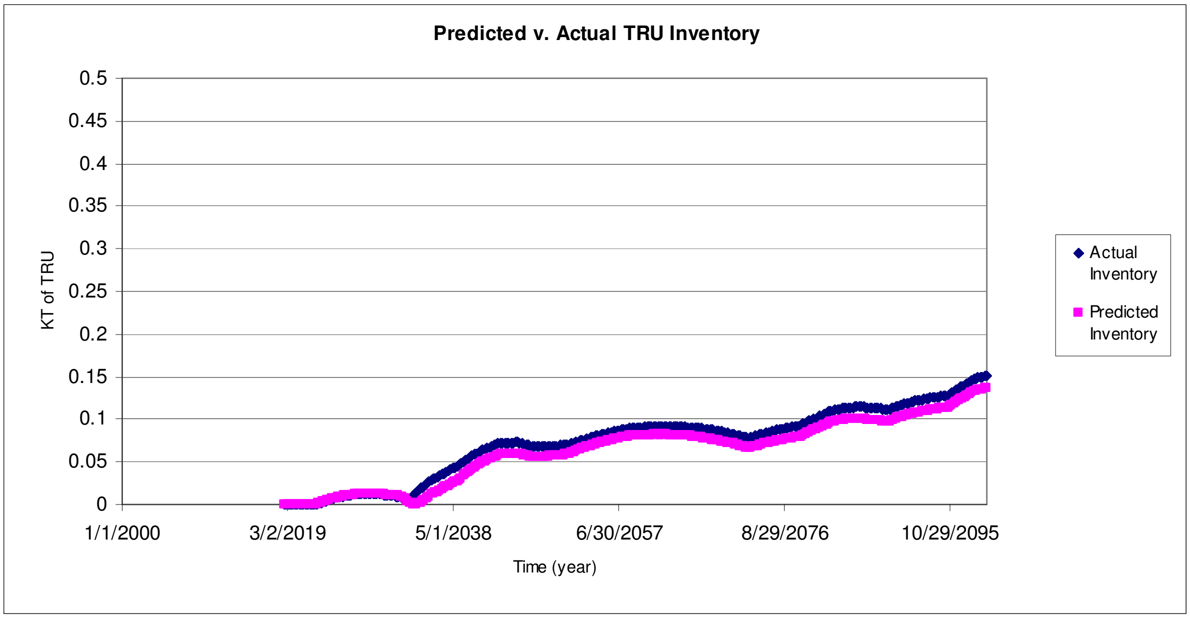

Figure 3-44: Case 2 Predicted v. Actual Inventory with a 1 Year Lead Time

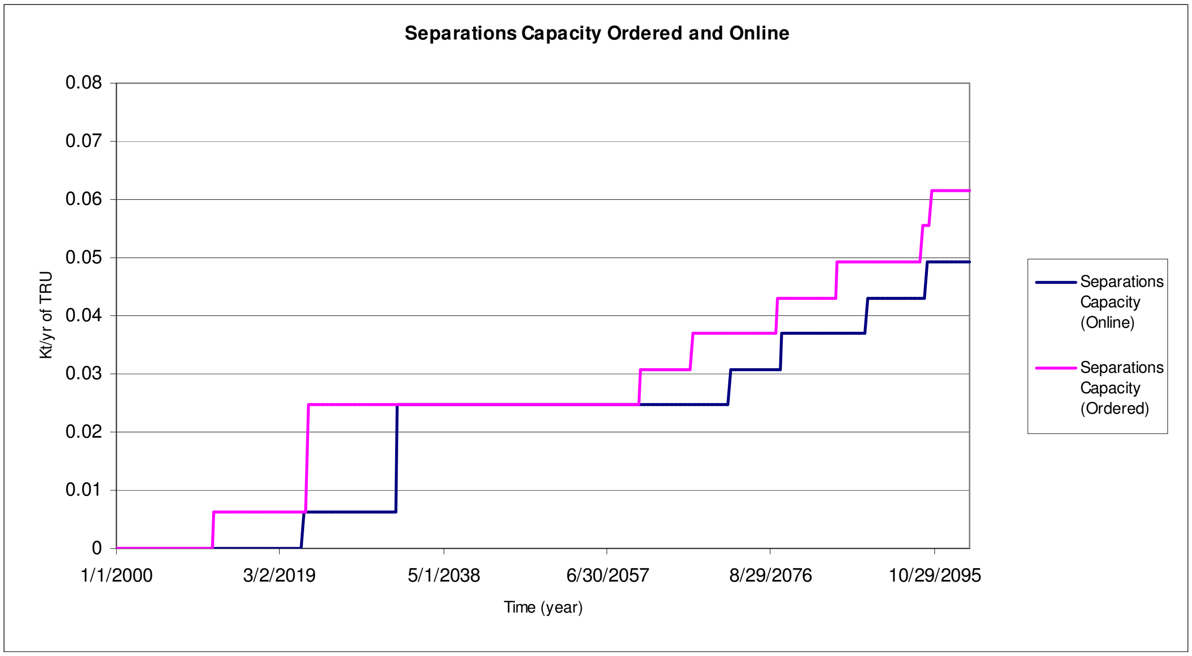

Figure 3-45: Case 2 Separations Capacity with a 1 Year Lead Time

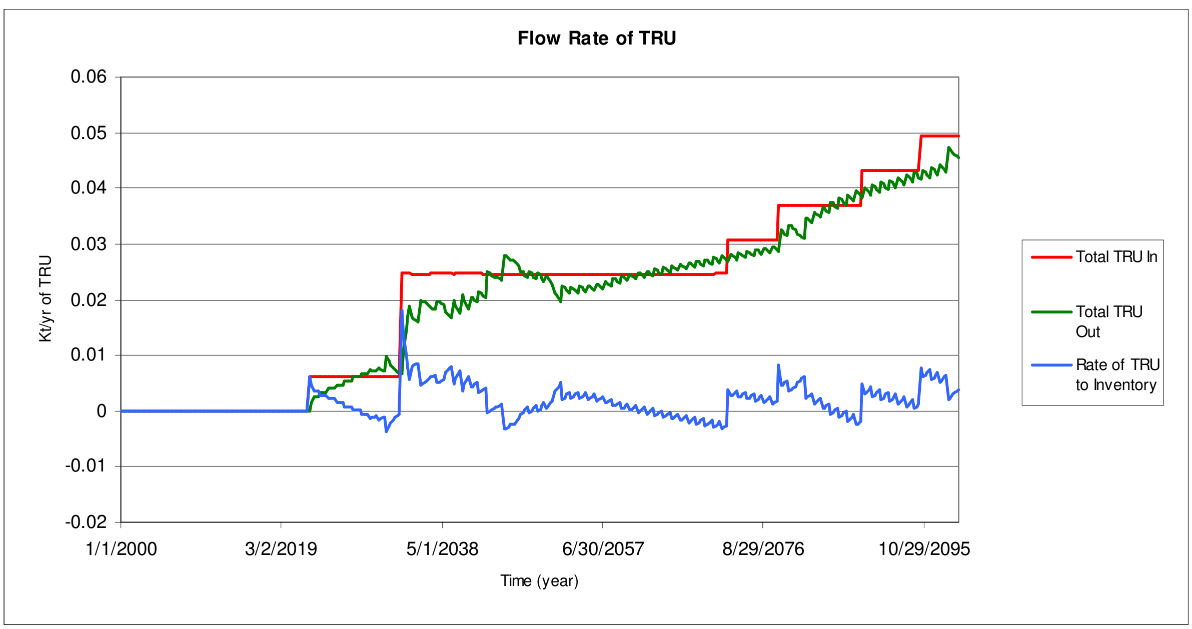

Figure 3-46: Case 2 Flow Rate of TRU to Predicted Inventory with a 1 Year Lead Time

3.2.1.3 Case 3 Separation Facility Size of 0.25 Kt/yr

Case 3 Summary

In the Case 3 scenario the separations facility size is further reduced to 0.25 Kt/yr of heavy metal. As a result the lead time of 3 years became the optimal build scenario because the build schedule is the most evenly spaced out and it has the smallest inventory. This follows the prediction that as the separations facility size decreases the lead time must increase. If the lead time is increased too much separations capacity is ordered (Figure 3-49, Figure 3-53 and Figure 3-57) which creates very large inventories (Figure 3-47, Figure 3-51 and Figure 3-55). If a smaller lead time is used then the separations facility will not come online early enough (compare Figure 3-61 – lead time of 3 years and Figure 3-65 – lead time of 1 year) to meet the demand (Figure 3-59 and Figure 3-63) and the system will start to request more facilities that will then create a large inventory later on in the simulation.

The data presented in Figure 3-47 - Figure 3-50, Figure 3-51 - Figure 3-54, Figure 3-55 - Figure 3-58, Figure 3-59 - Figure 3-62, and Figure 3-63 - Figure 3-66 present the data for Case 3 with separation lead times of 7 years, 5 years, 4 years, 3 years, and 1 year, respectively.

Lead Time of 7 Years

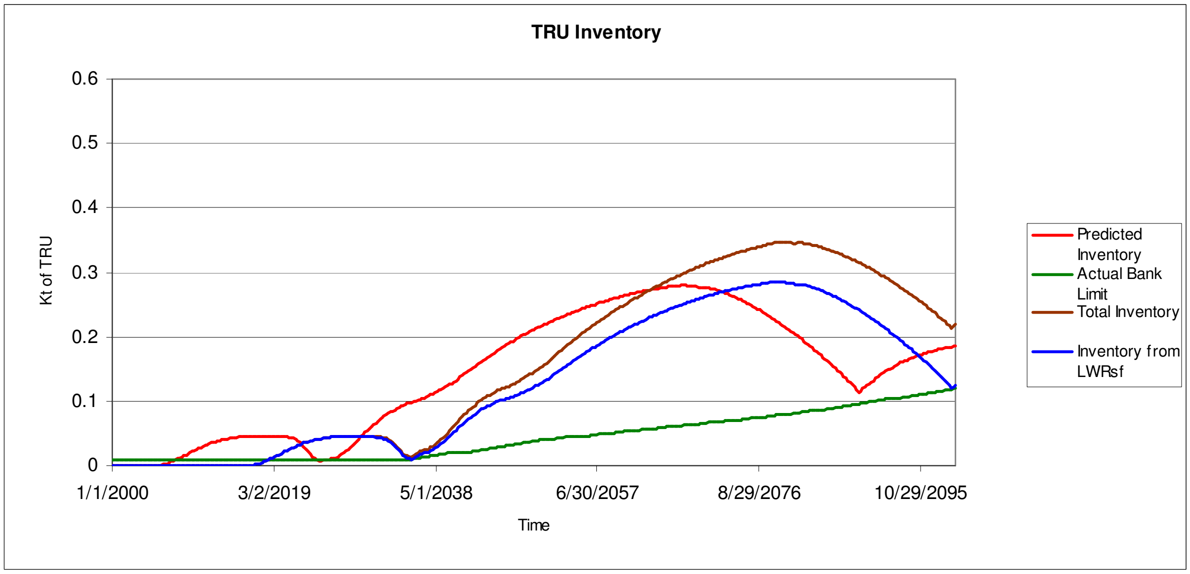

Figure 3-47: Case 3 TRU Inventory with 7 Year Lead Time

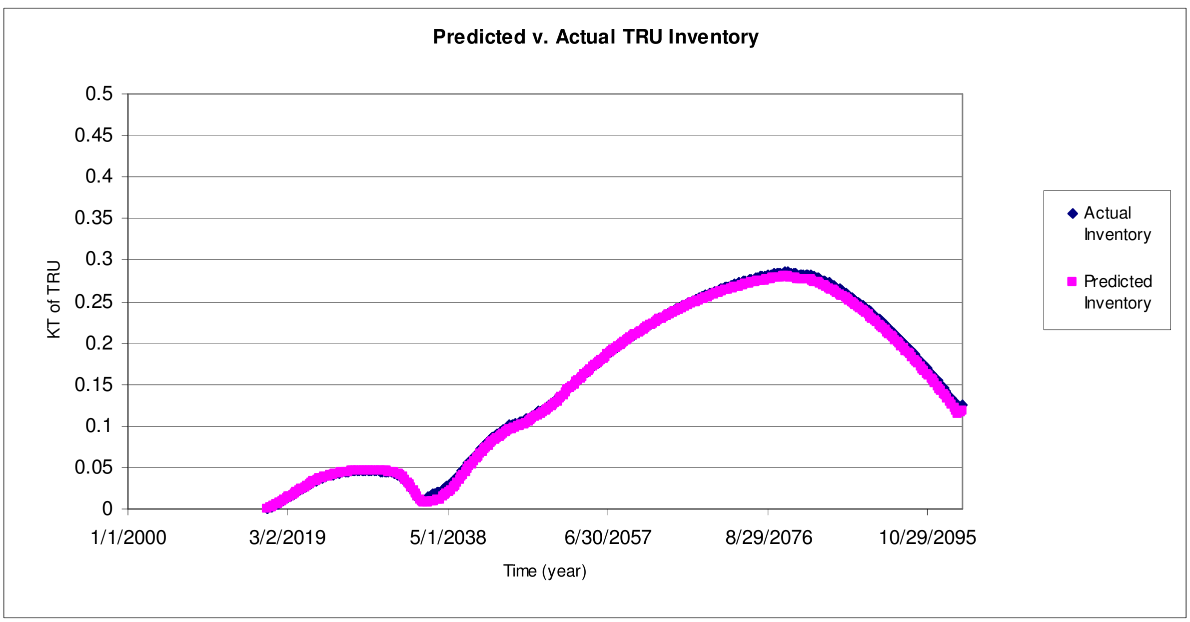

Figure 3-48: Case 3 Predicted v. Actual Inventory with 7 Year Lead Time

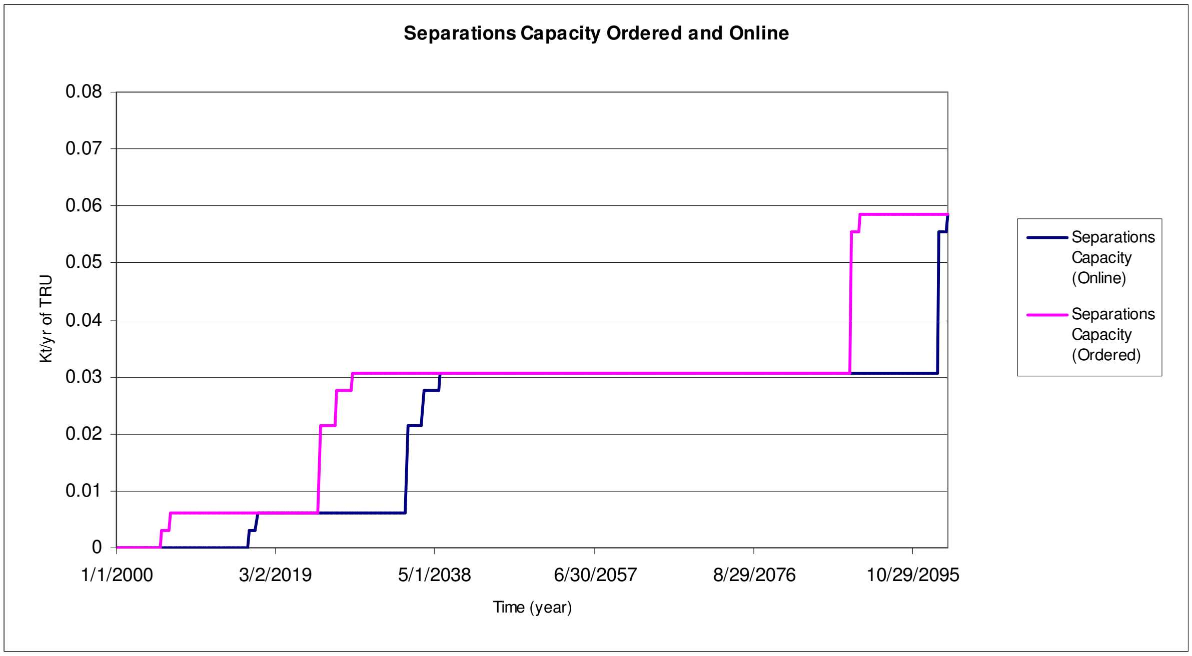

Figure 3-49: Case 3 Separation Capacity (Kt/yr of TRU) with 7 Year Lead Time

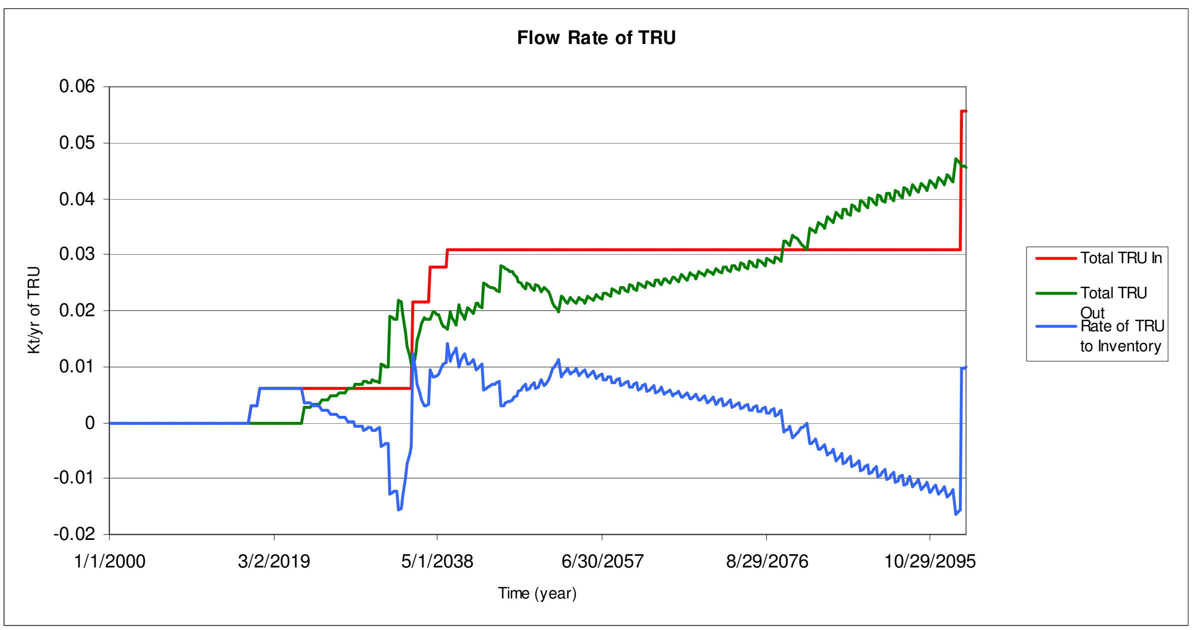

Figure 3-50: Case 3 Flow Rate of TRU to Predicted Inventory with a 7 Year Lead Time

Lead Time of 5 Years

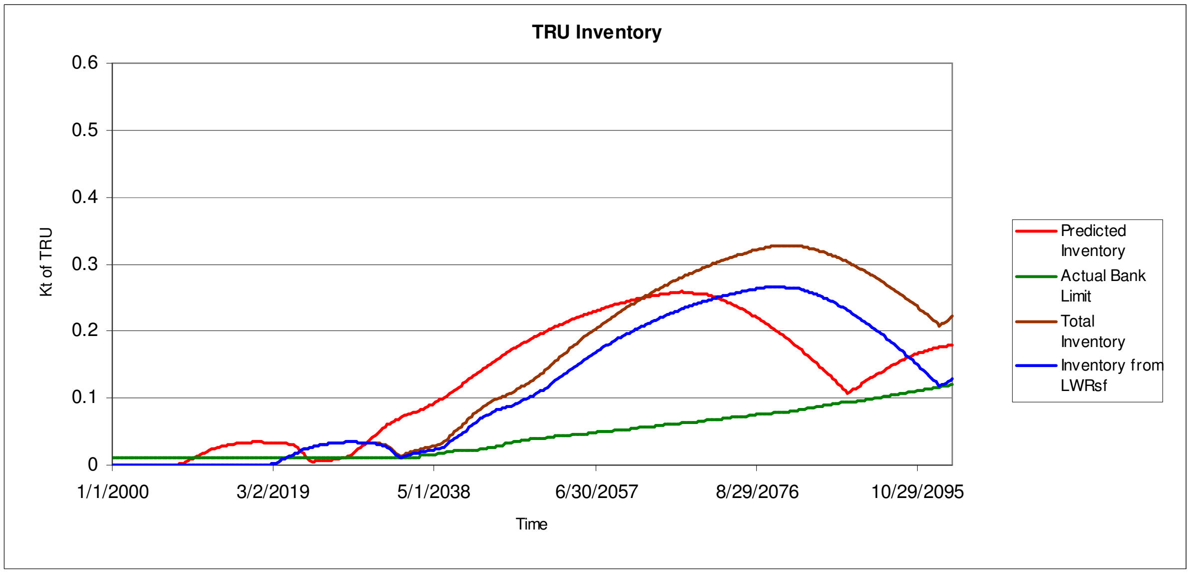

Figure 3-51: Case 3 TRU Inventory with a Lead Time of 5 Years

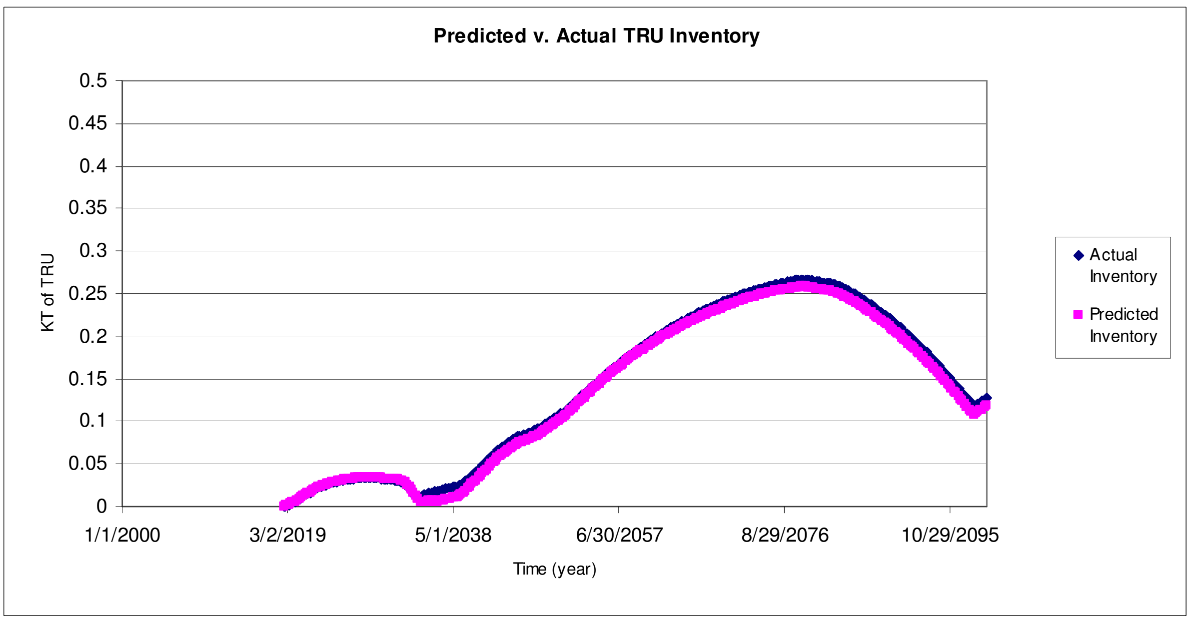

Figure 3-52: Case 3 Predicted v. Actual Inventory with a Lead Time of 5 Years

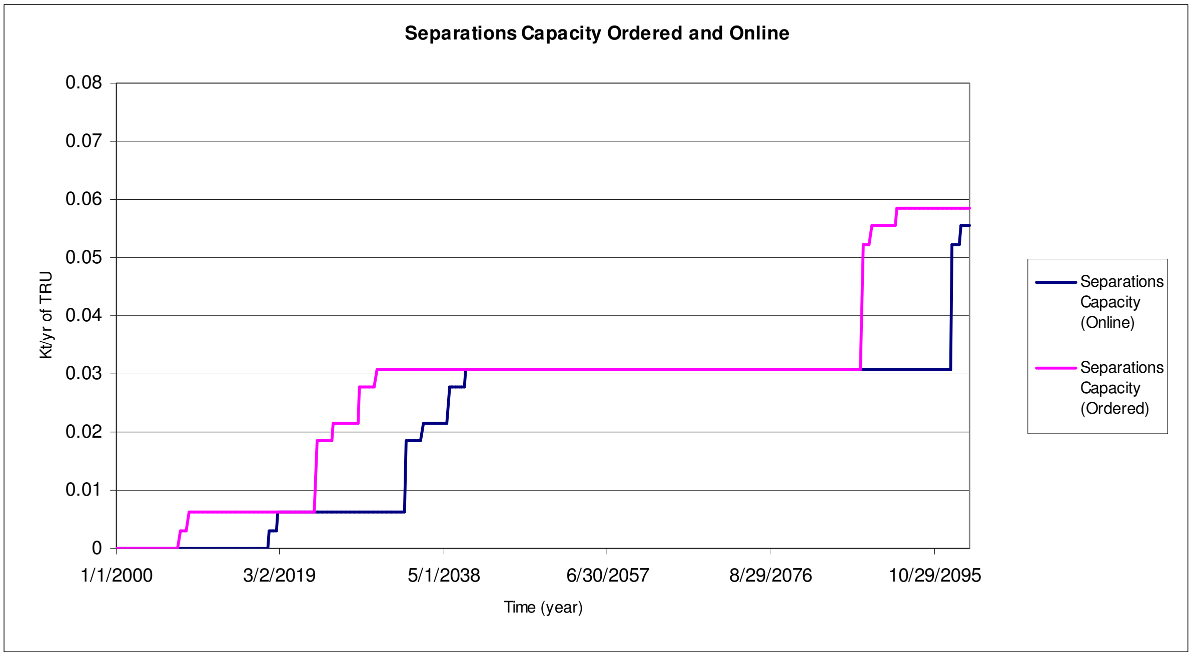

Figure 3-53: Case 3 Separations Capacity (kt/yr) with a Lead Time of 5 Years

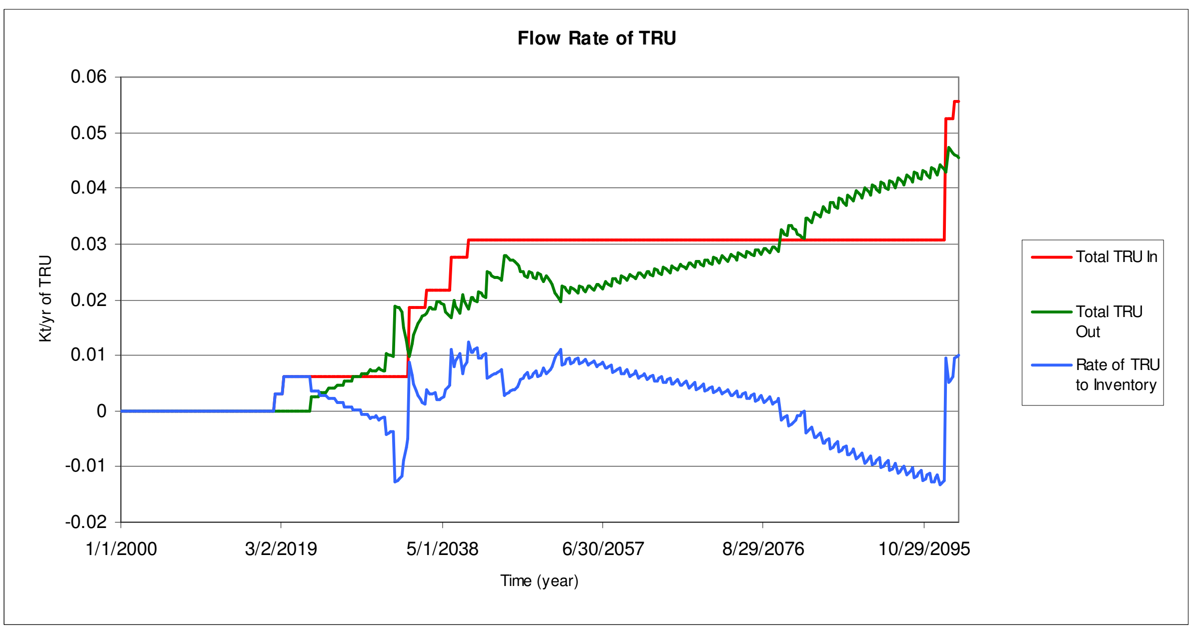

Figure 3-54: Case 3 Flow Rate of TRU to Inventory with a Lead Time of 5 Years

Lead Time of 4 Years

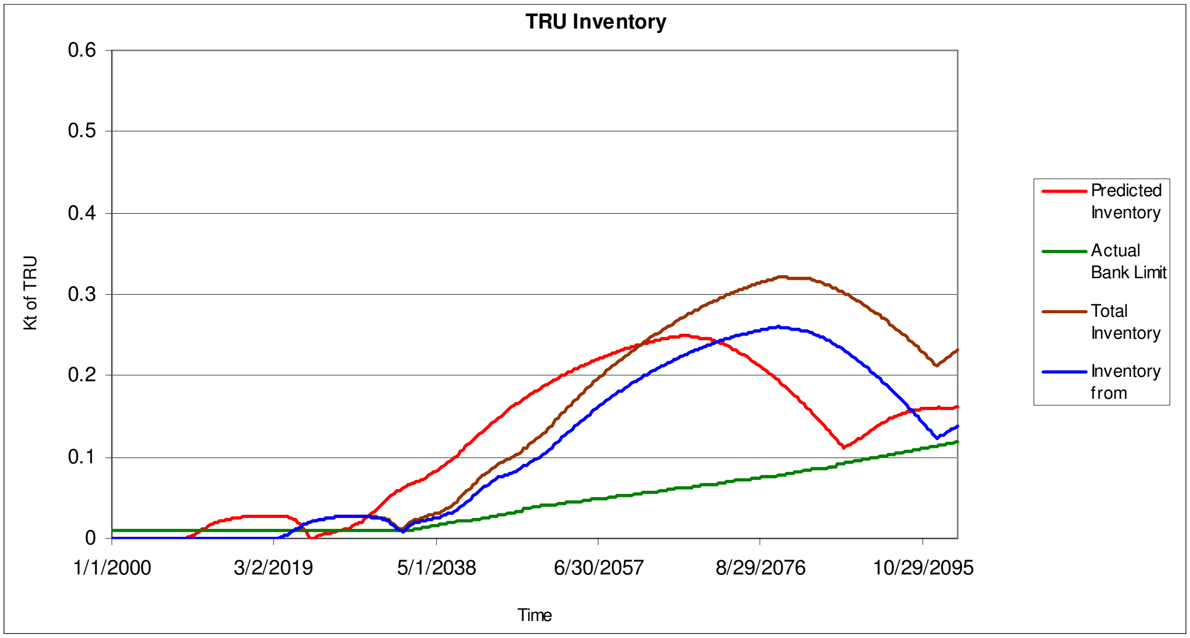

Figure 3-55: Case 3 TRU Inventory with a Lead Time of 4 Years

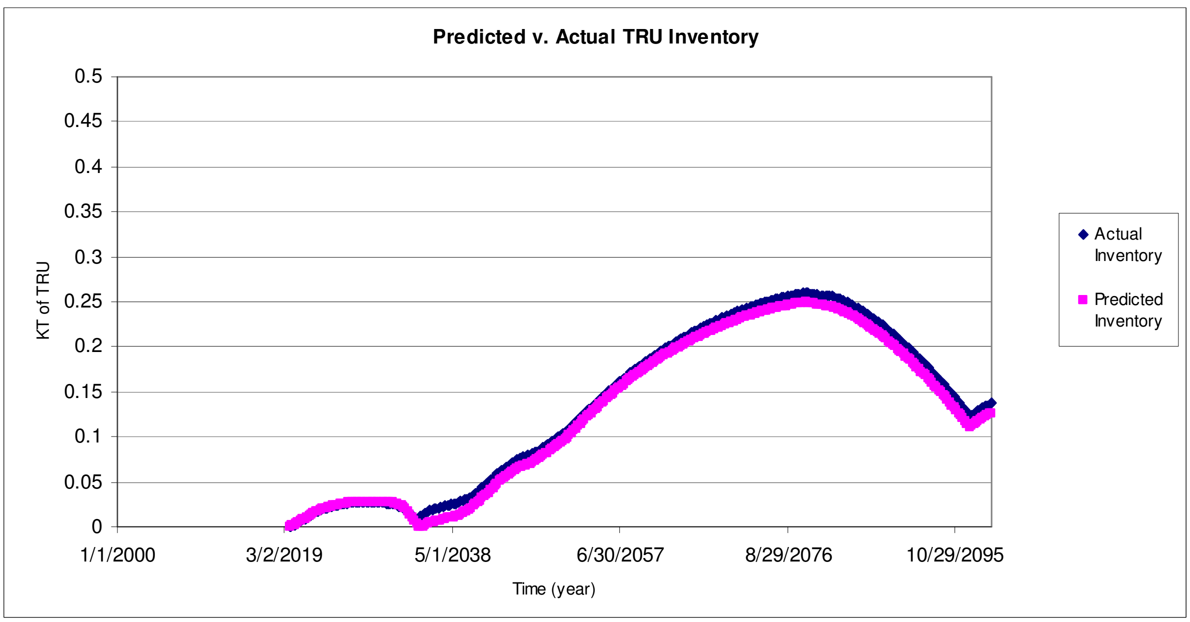

Figure 3-56: Case 3 Predicted v. Actual Inventory with a 4 Year Lead Time

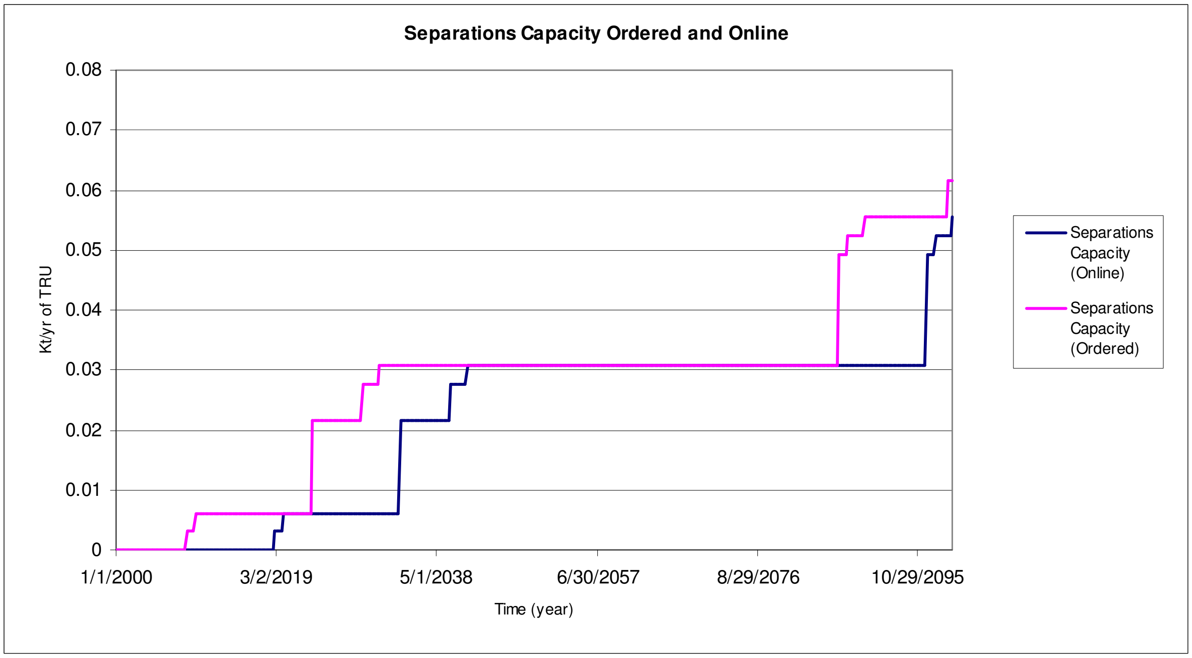

Figure 3-57: Case 3 Separations Capacity (kt/yr) with a 4 Year Lead Time

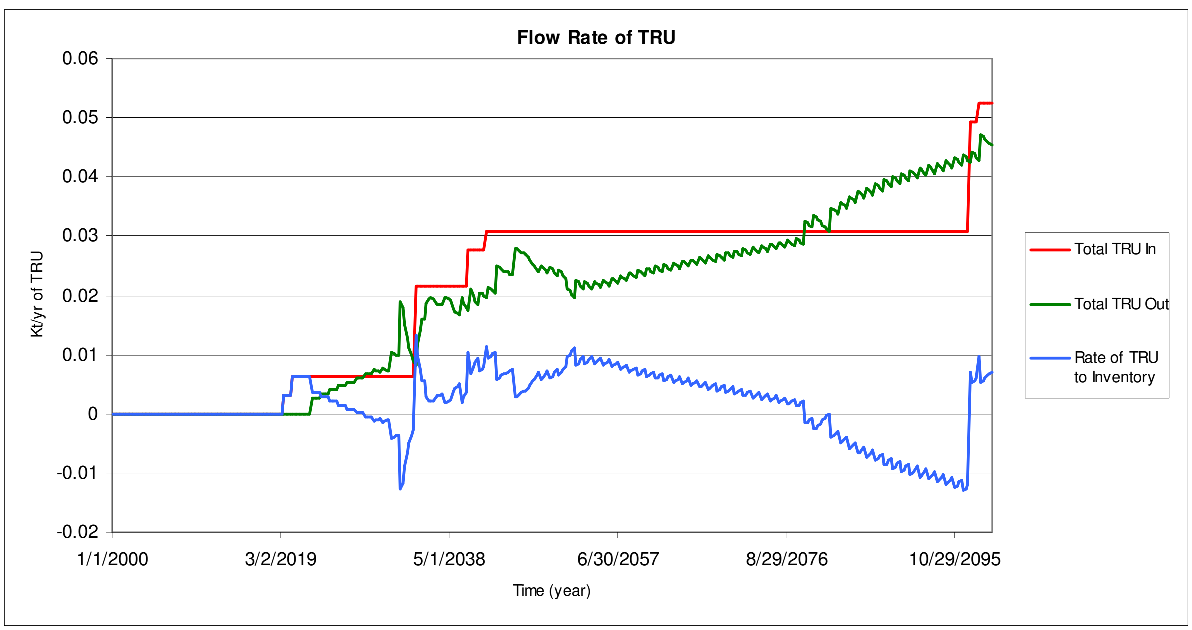

Figure 3-58: Case 3 Flow Rate of TRU to Predicted Inventory with a 4 Year Lead Time

Lead Time of 3 Years

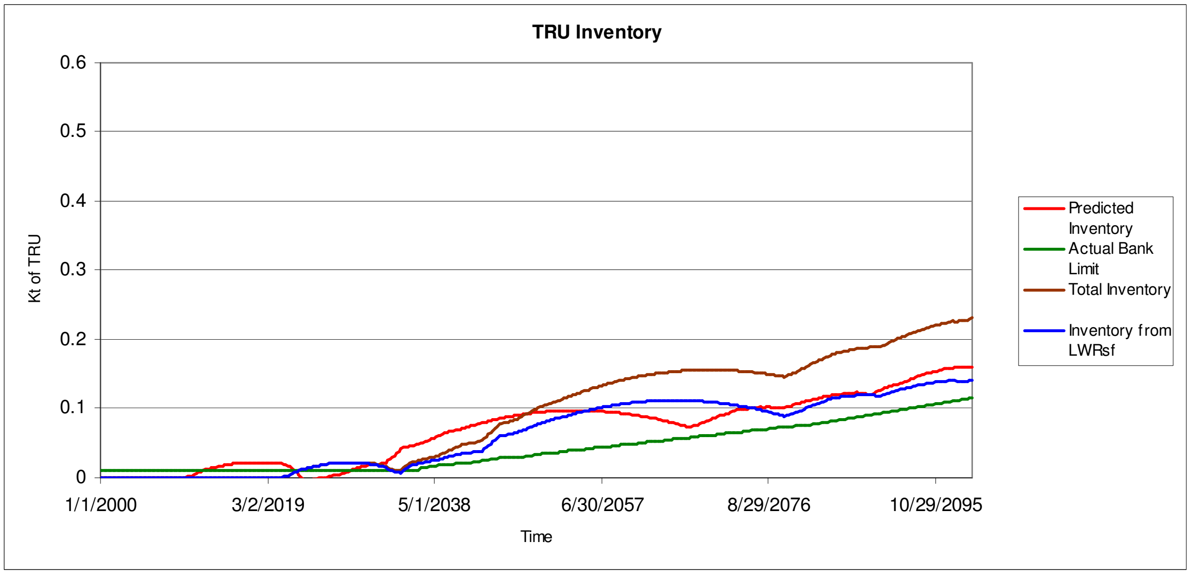

Figure 3-59: Case 3 TRU Inventory with a Lead Time of 3 Years

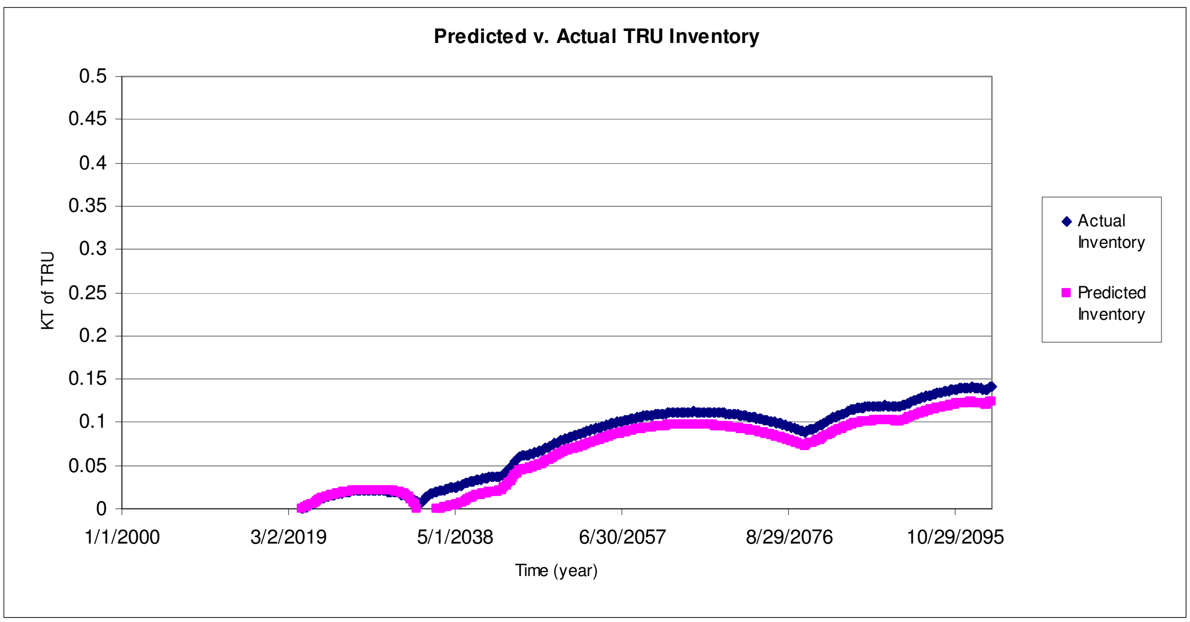

Figure 3-60: Case 3 Predicted v. Actual Inventory with a 3 Year Lead Time

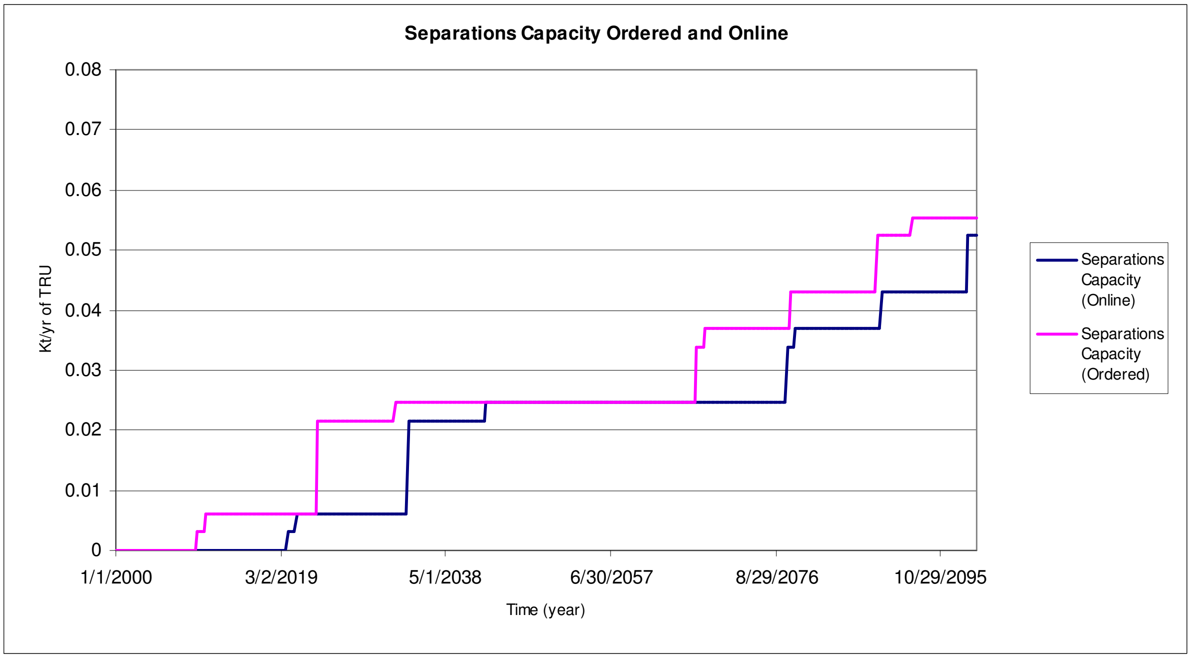

Figure 3-61: Case 3 Separations Capacity (kt/yr) with a Lead Time of 3 Years

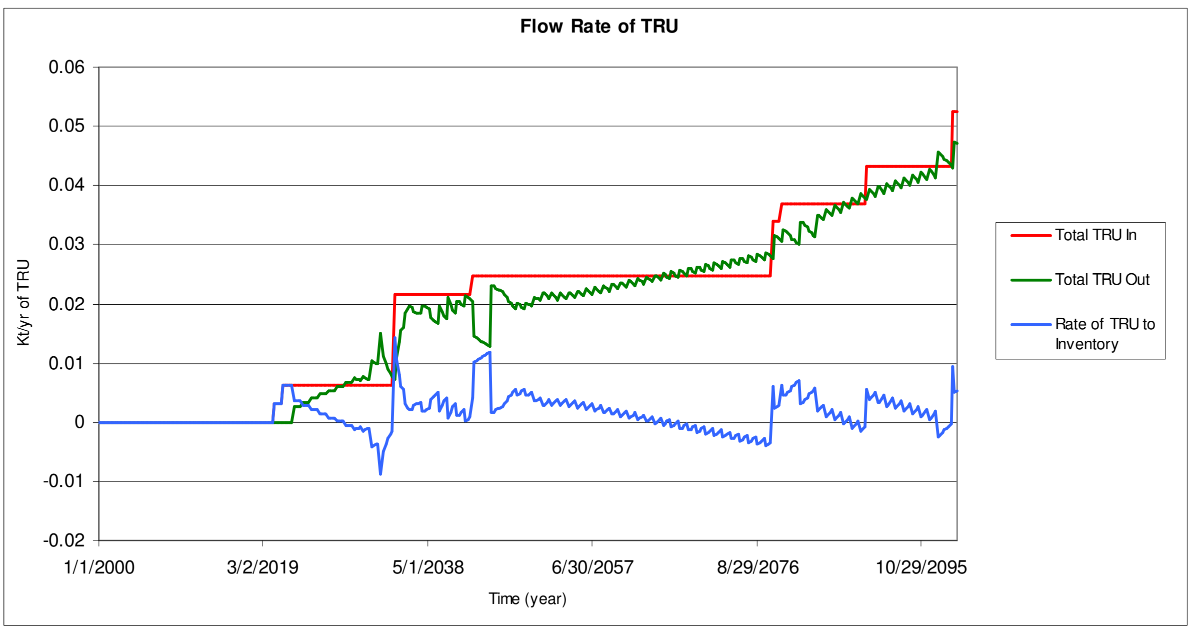

Figure 3-62: Case 3 Flow Rate of TRU to Predicted Inventory with a 3 Year Lead Time

Lead Time of 1 Year

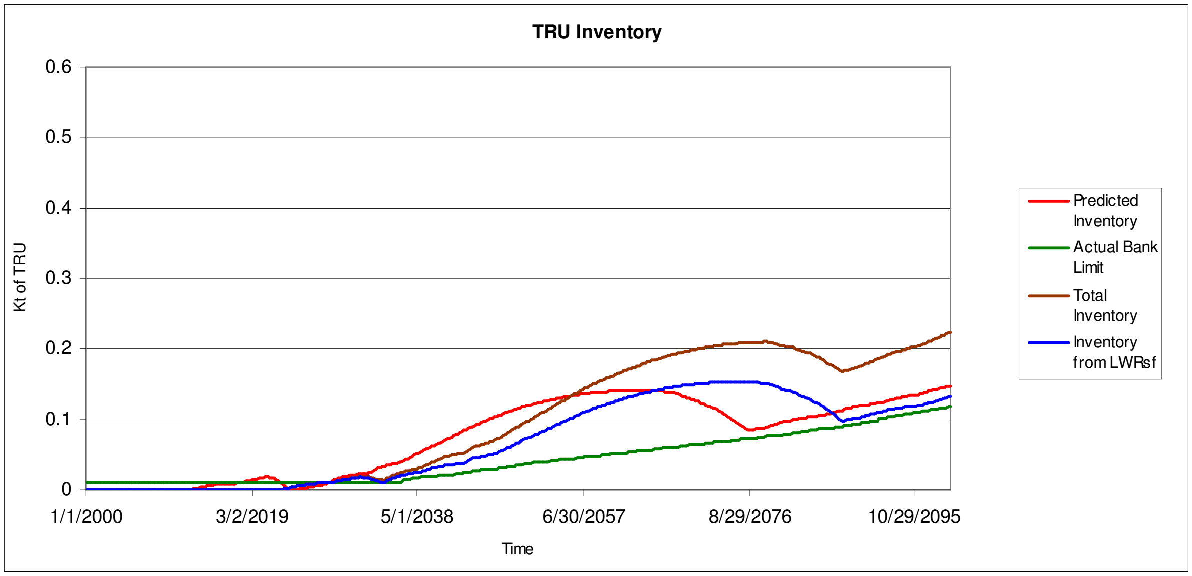

Figure 3-63: Case 3 TRU Inventory with a 1 Year Lead Time

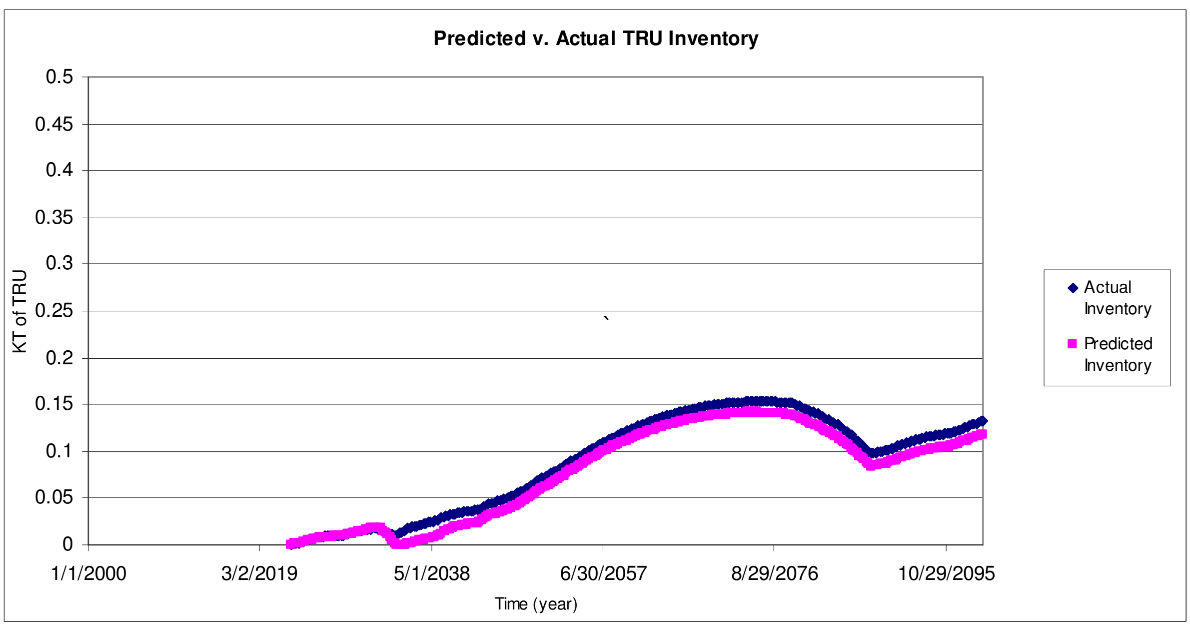

Figure 3-64: Case 3 Predicted v. Actual Inventory with 1 Year Lead Time

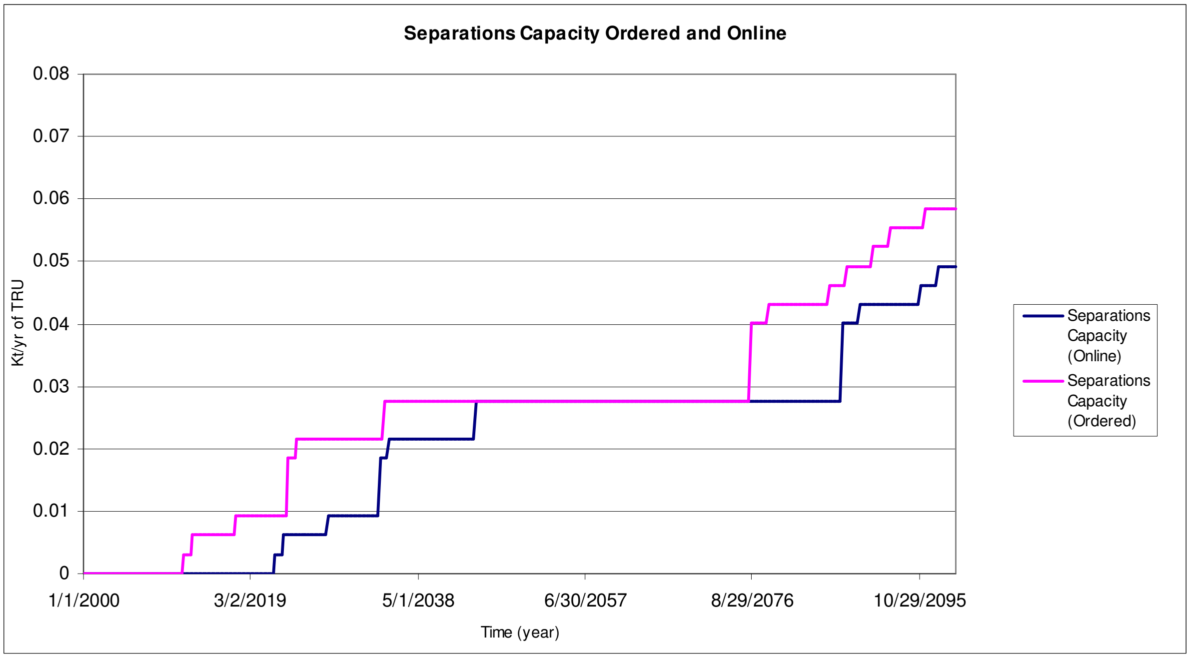

Figure 3-65: Case 3 Separations Capacity (kt/yr) with 1 Year Lead Time

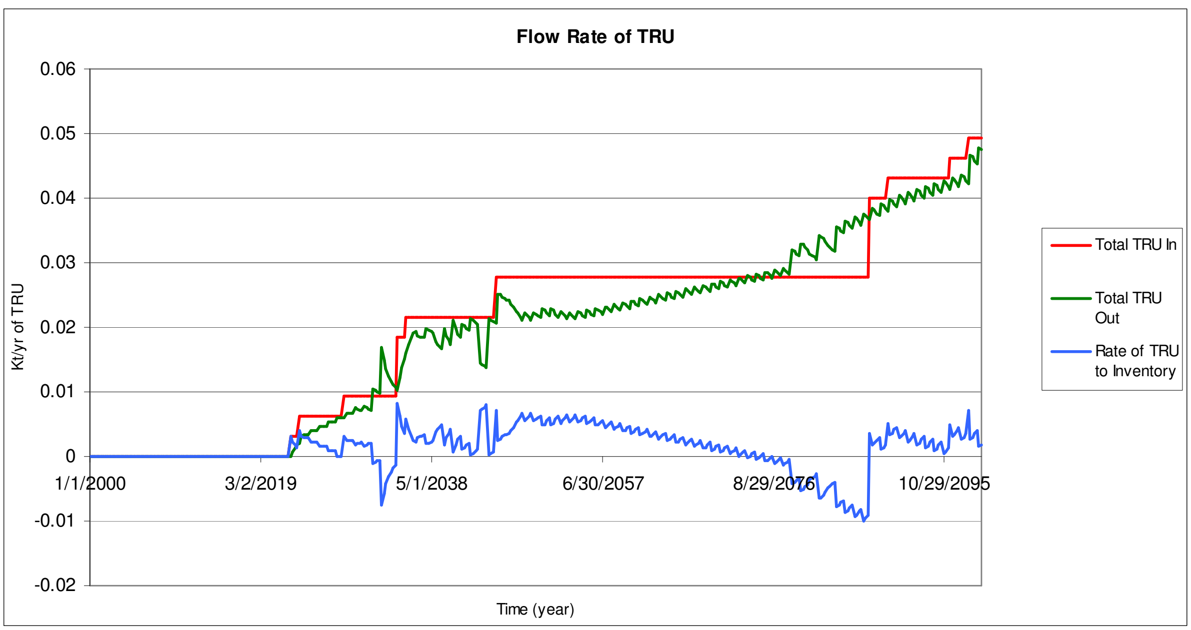

Figure 3-66: Case 3 Flow Rate of TRU to Predicted Inventory with 1 Year Lead Time

The results from Section 3.2.1 show that the optimal scenarios with FBR growth of 10% are for a separation facility size of 0.5 Kt/yr and a lead time of 1 year or a separation facility size of 0.25 Kt/yr and a lead time of 3 years. The 1 Kt/yr separation facility (Case 1) was not very good for this growth rate because this facility was too large for the small growth of FBRs and caused large inventories of separated material. Even with a zero year lead time the same results were obtained. With this type of growth rate the largest separation facility size should be 0.5 Kt/yr because it only requires one year lead time.

3.2.2 New FBR Held at 20% of Growth Rate

In the following cases the FBR growth rate will be limited to 20% of the energy growth per year. Separation facilities and lead times will be varied in order to determine the most optimal build scenario. Figure 3-67 and Figure 3-68 show the operating reactors and the deployed reactor capacity for a 20% FBR growth rate.

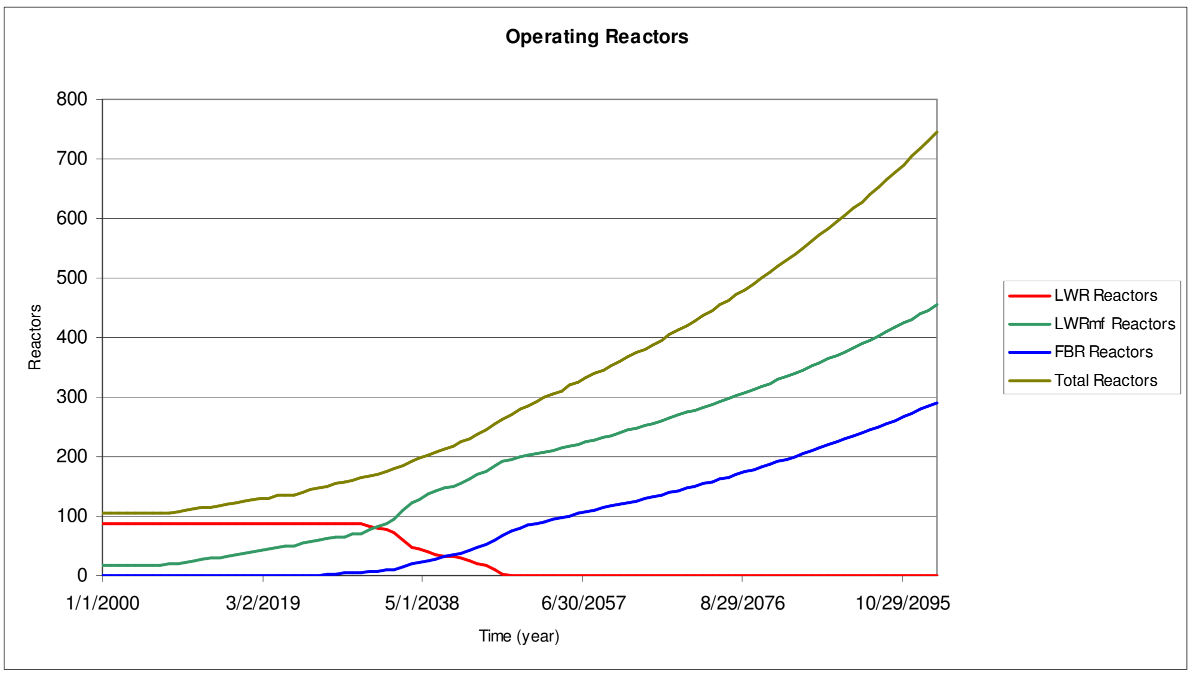

Figure 3-67: Case 4 Operating Reactors

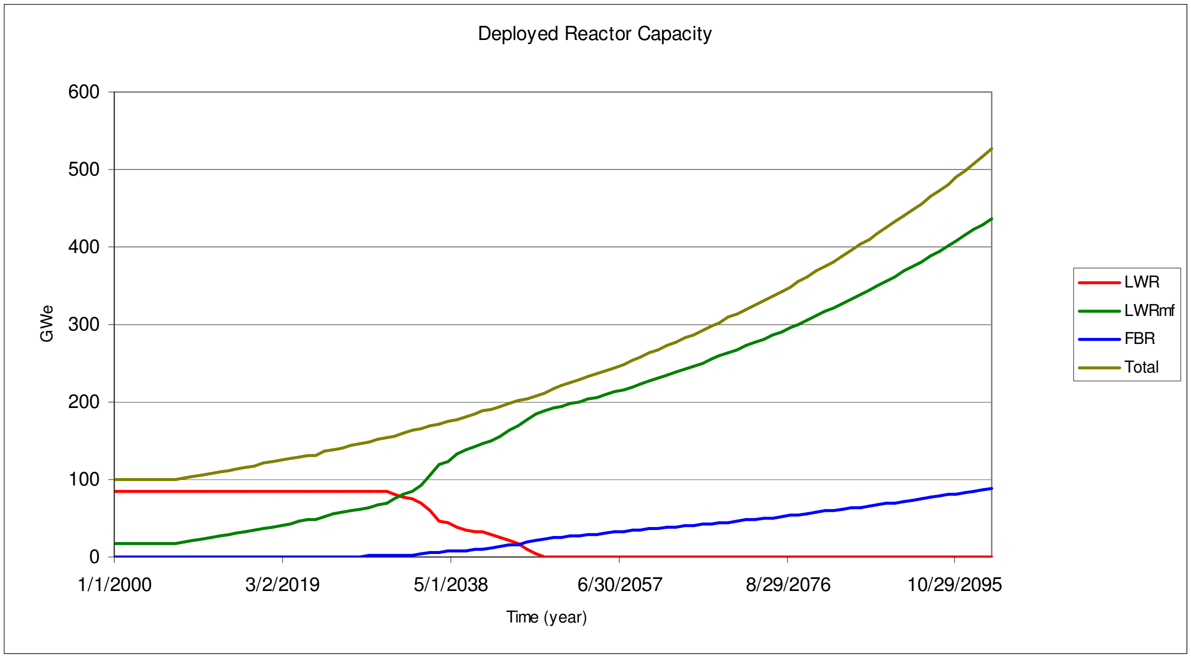

Figure 3-68: Case 4 Deployed Reactor Capacity

3.2.2.1 Case 4 Separation Facility Size of 1 Kt/yr

Summary of Case 4

Each change in lead time for Case 4 is very similar due to the large separation capacity that comes online with each new separation facility. The best building scenario is with a lead time of 1 year. This produces the smallest overall TRU inventory and a fairly spread out separations capacity build rate (Figure 3-85 and Figure 3-87). The 7 year lead time scenario produces a very large initial inventory (Figure 3-69), which will allow the system to delay building new facilities for a longer time. Then when it is time to build new facilities several new facilities are required, which cause a very large increase in the separated material inventory (Figure 3-69 and Figure 3-71).

The data presented in Figure 3-69 - Figure 3-72, Figure 3-73 - Figure 3-76, Figure 3-77 - Figure 3-80, Figure 3-81 - Figure 3-84, and Figure 3-85 - Figure 3-88 show the results for lead times of 7 years, 5 years, 4 years, 3 years, and 1 year, respectively.

Lead Time of 7 Years

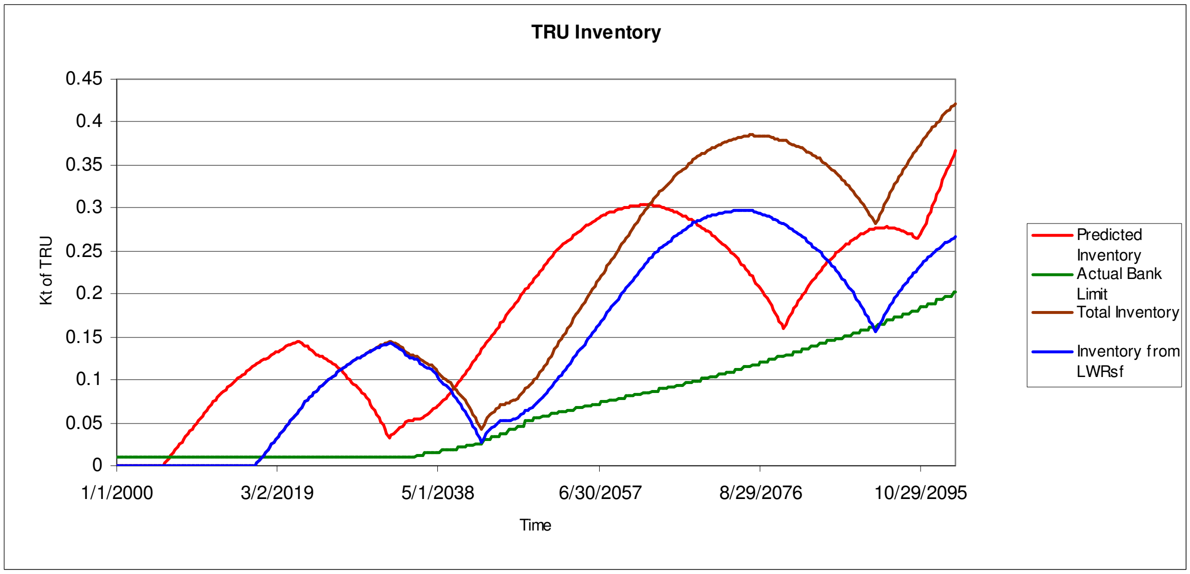

Figure 3-69: Case 4 TRU Inventory with 7 Year Lead Time

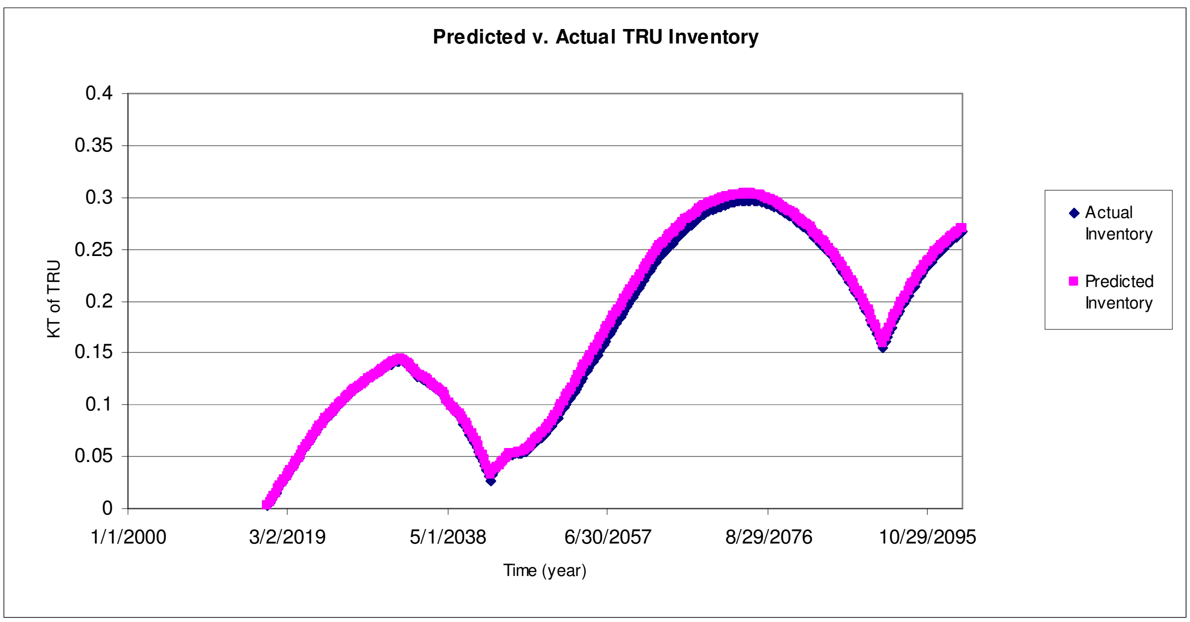

Figure 3-70: Case 4 Predicted v. Actual Inventory with 7 Year Lead Time

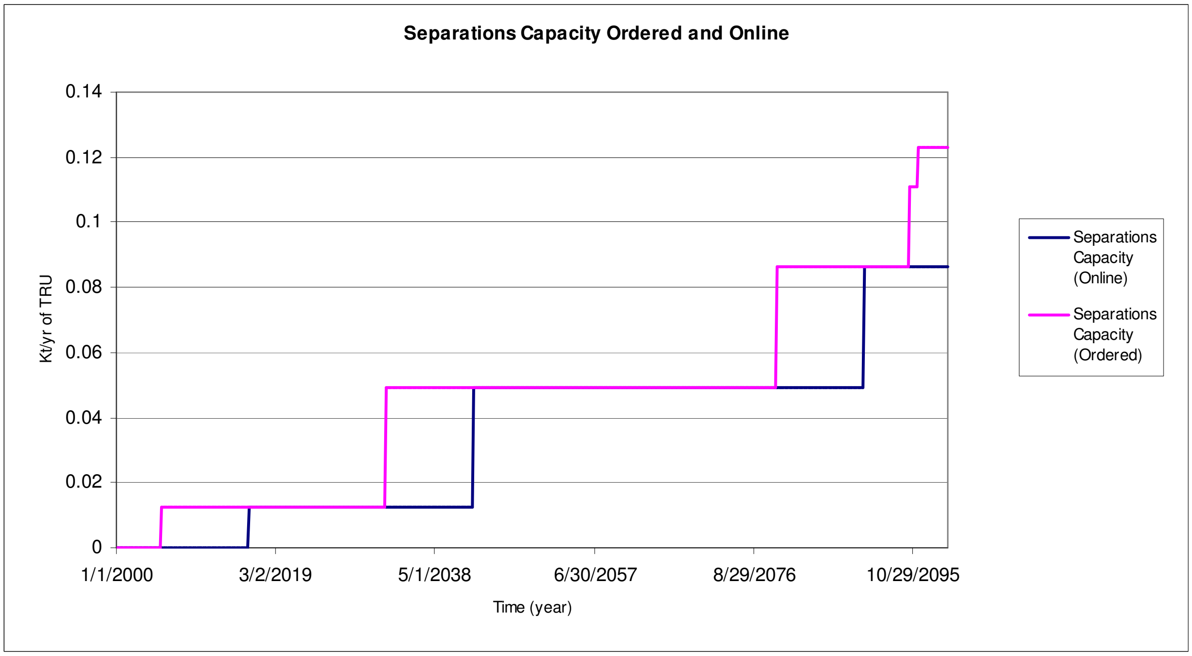

Figure 3-71: Case 4 Separations Capacity (kt/yr) with 7 Year Lead Time

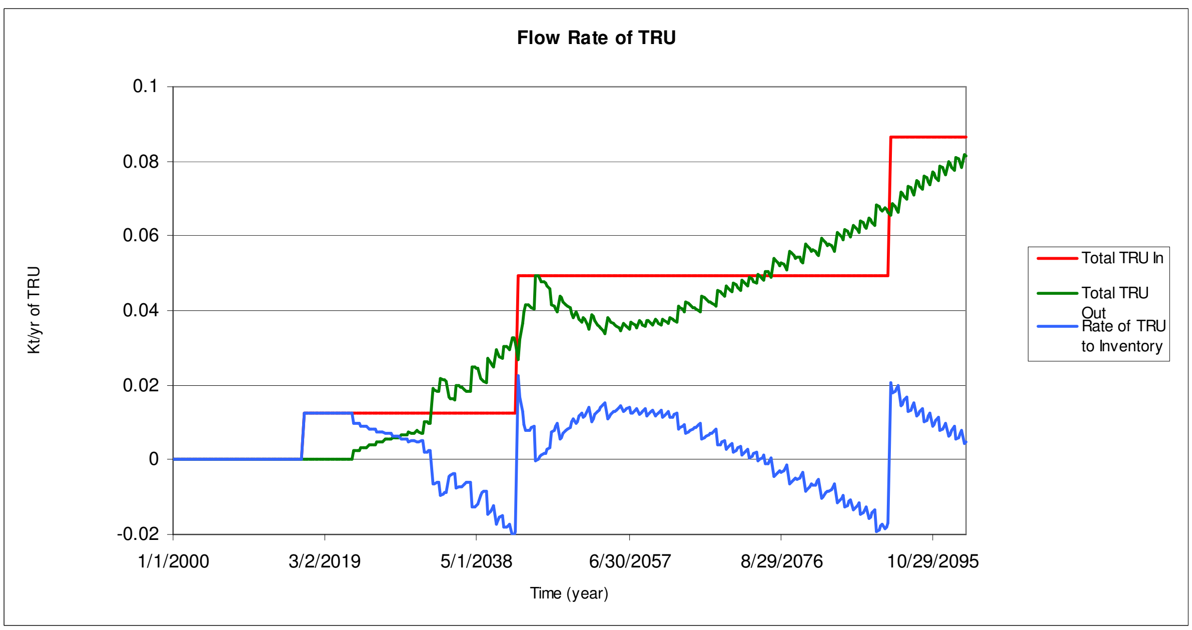

Figure 3-72: Case 4 Flow Rate of TRU to Predicted Inventory with 7 Year Lead Time

Lead Time of 5 Years

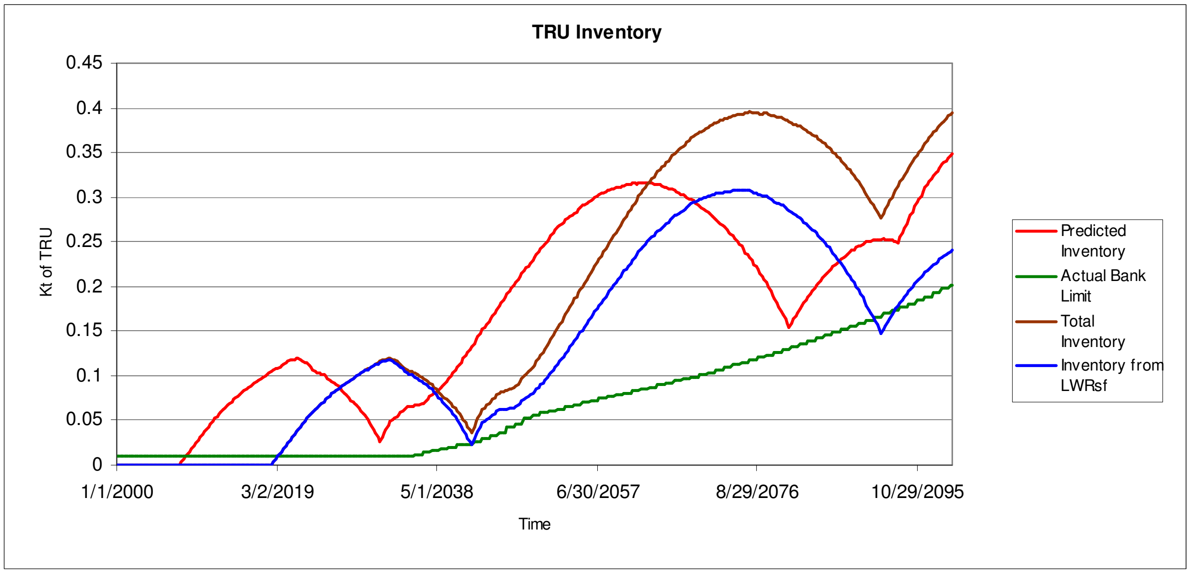

Figure 3-73: Case 4 TRU Inventory with 5 Year Lead Time

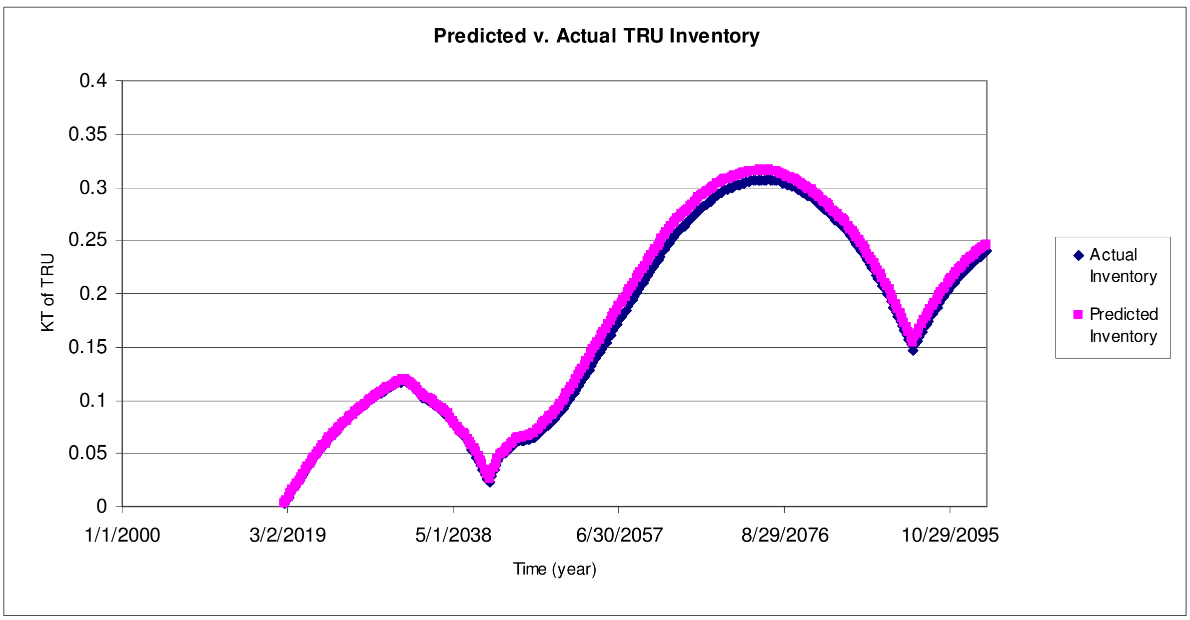

Figure 3-74: Case 4 Predicted v. Actual Inventory with 5 Year Lead Time

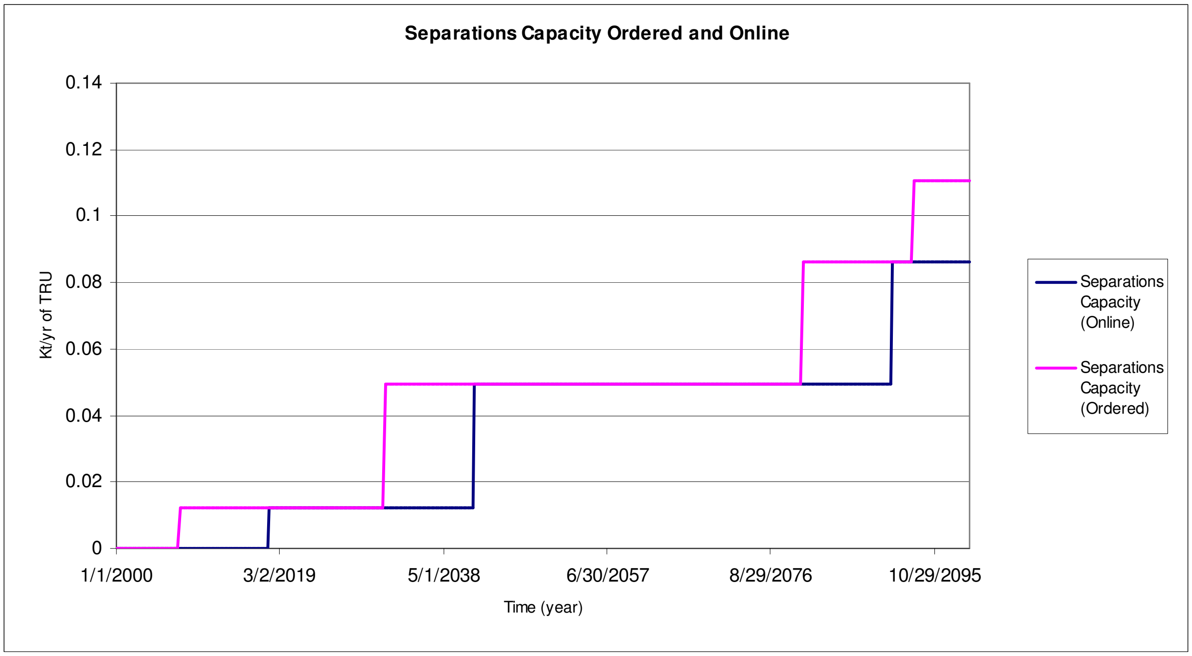

Figure 3-75: Case 4 Separations Capacity (kt/yr) with 5 Year Lead Time

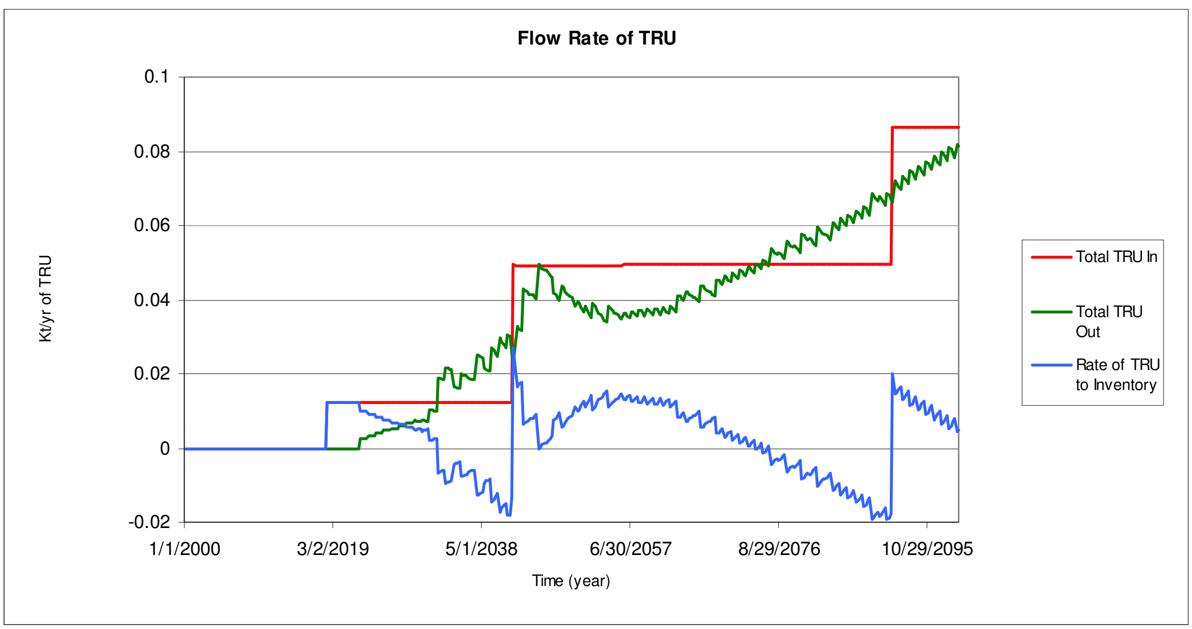

Figure 3-76: Case 4: Flow Rate of TRU to Predicted Inventory with 5 Year Lead Time

Lead Time of 4 Years

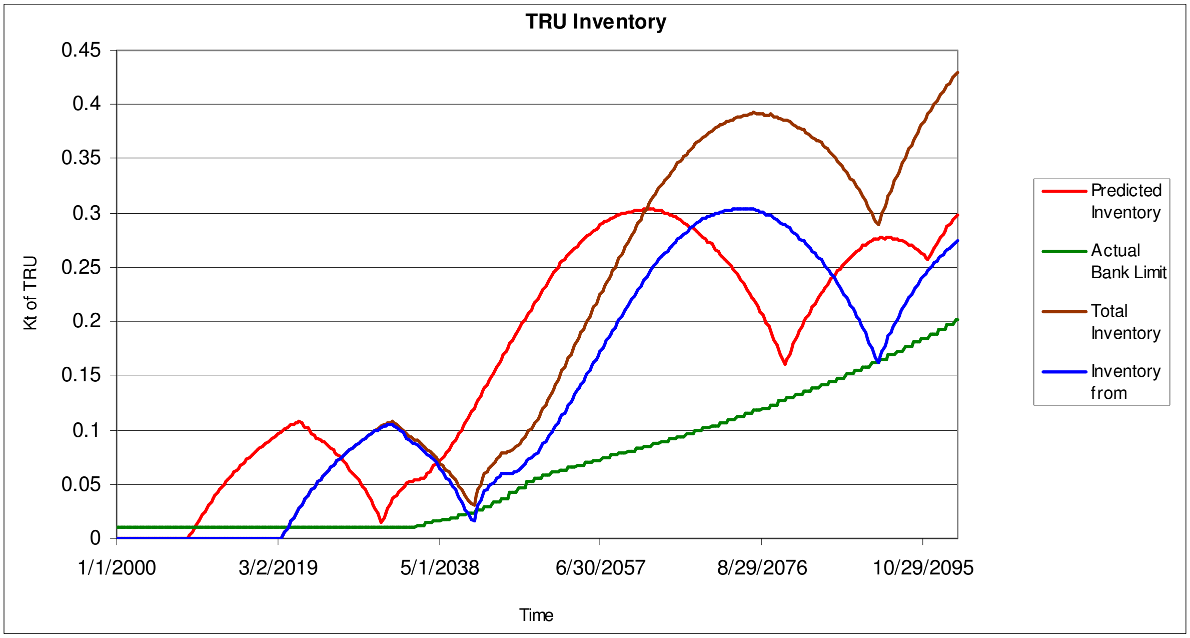

Figure 3-77: Case 4 TRU Inventory with 4 year Lead Time

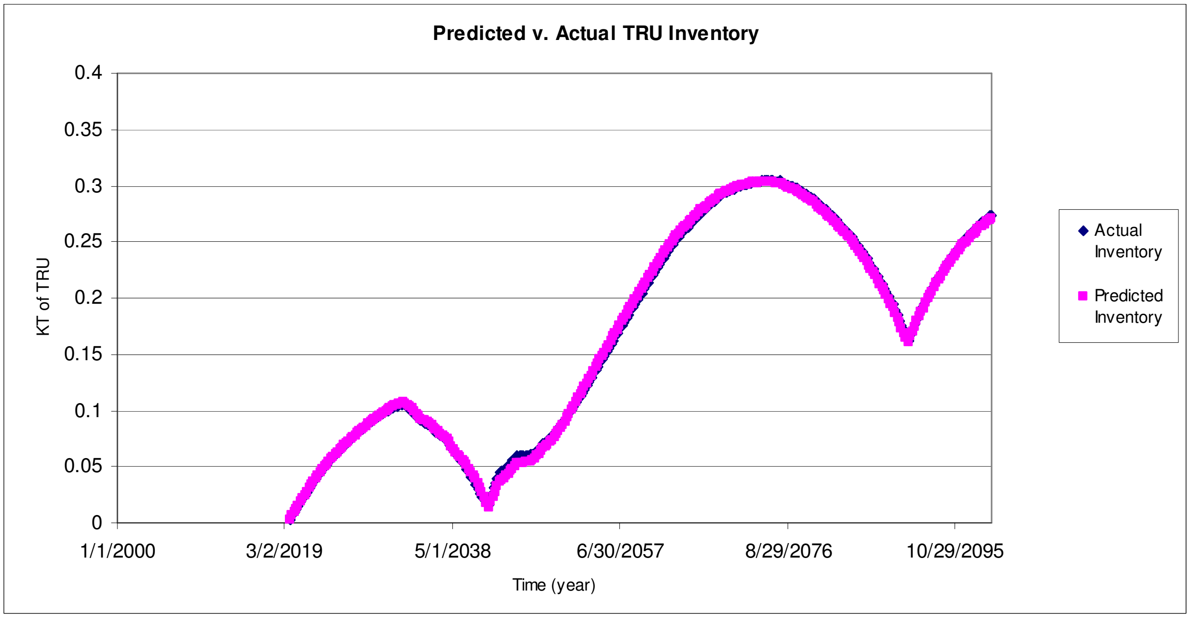

Figure 3-78: Case 4 Predicted v. Actual Inventory with 4 Year Lead Time

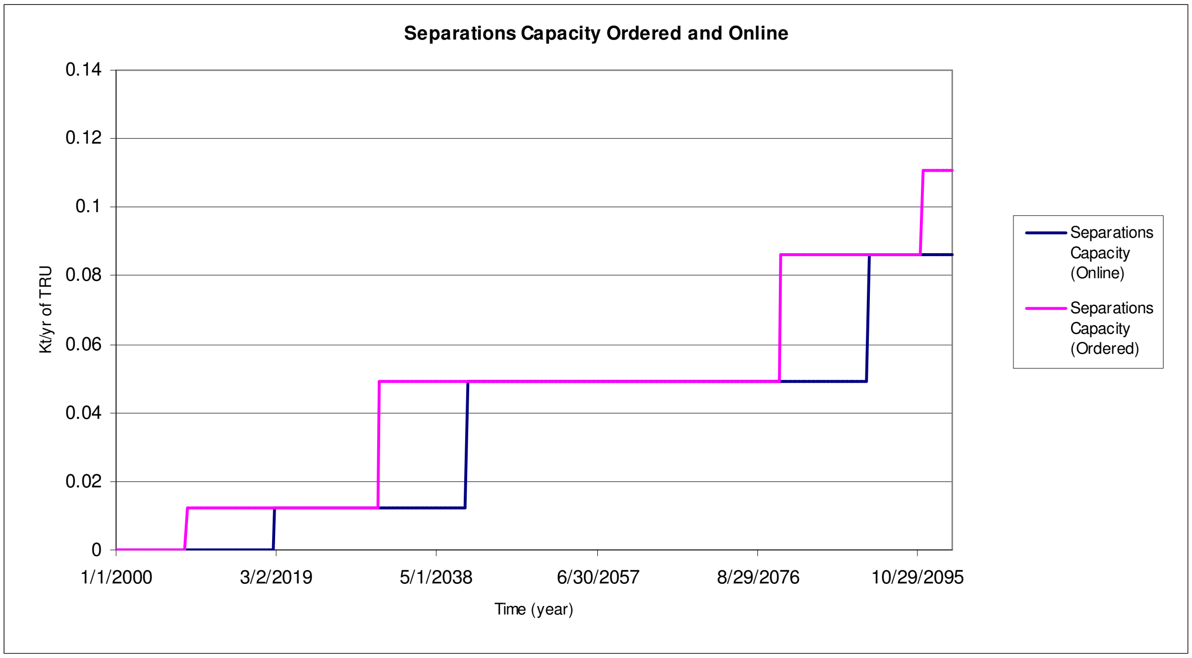

Figure 3-79: Case 4 Separations Capacity (kt/yr) with 4 Year Lead Time

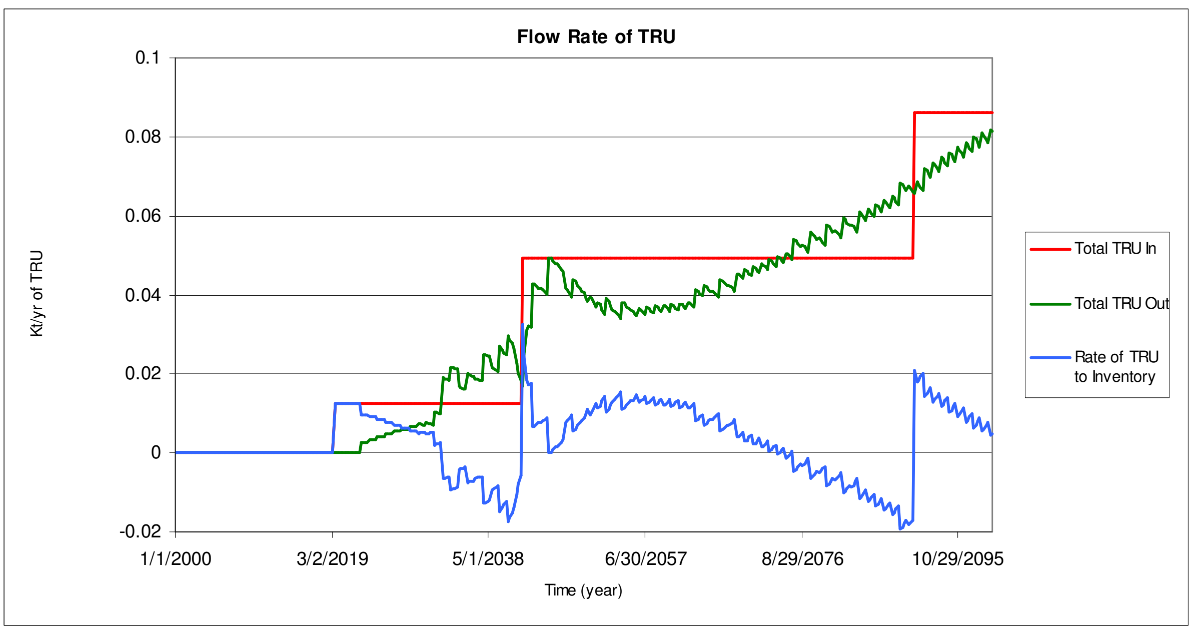

Figure 3-80: Case 4 Flow Rate of TRU to Predicted Inventory with 4 Year Lead Time

Lead Time of 3 Years

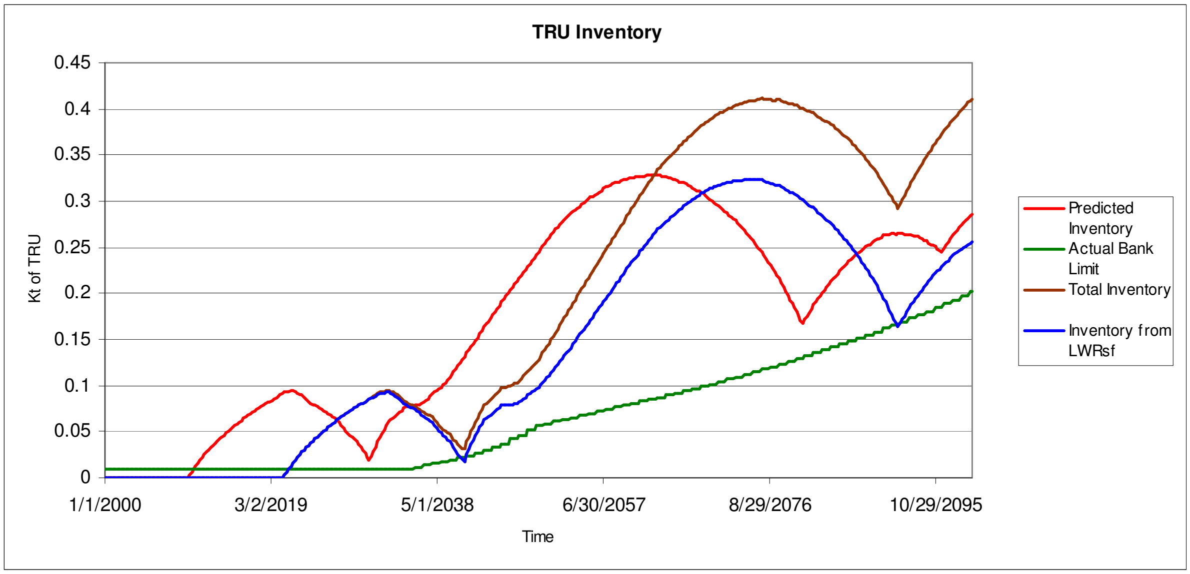

Figure 3-81: Case 4 TRU Inventory with 3 Year Lead Time

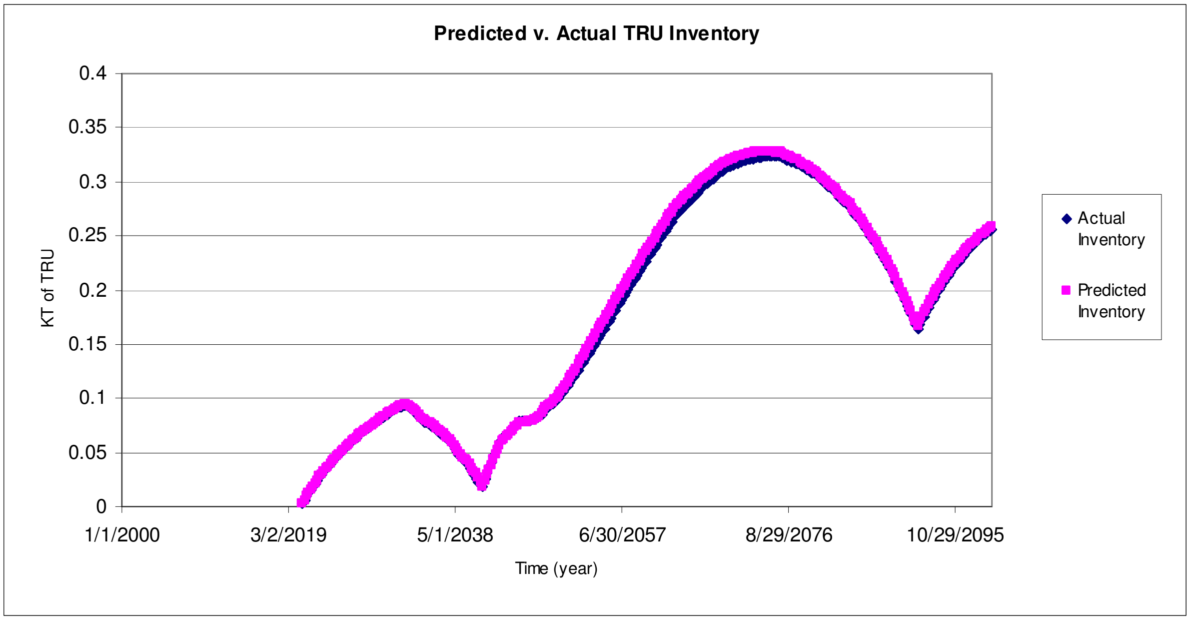

Figure 3-82: Case 4 Predicted v. Actual Inventory with 3 Year Lead Time

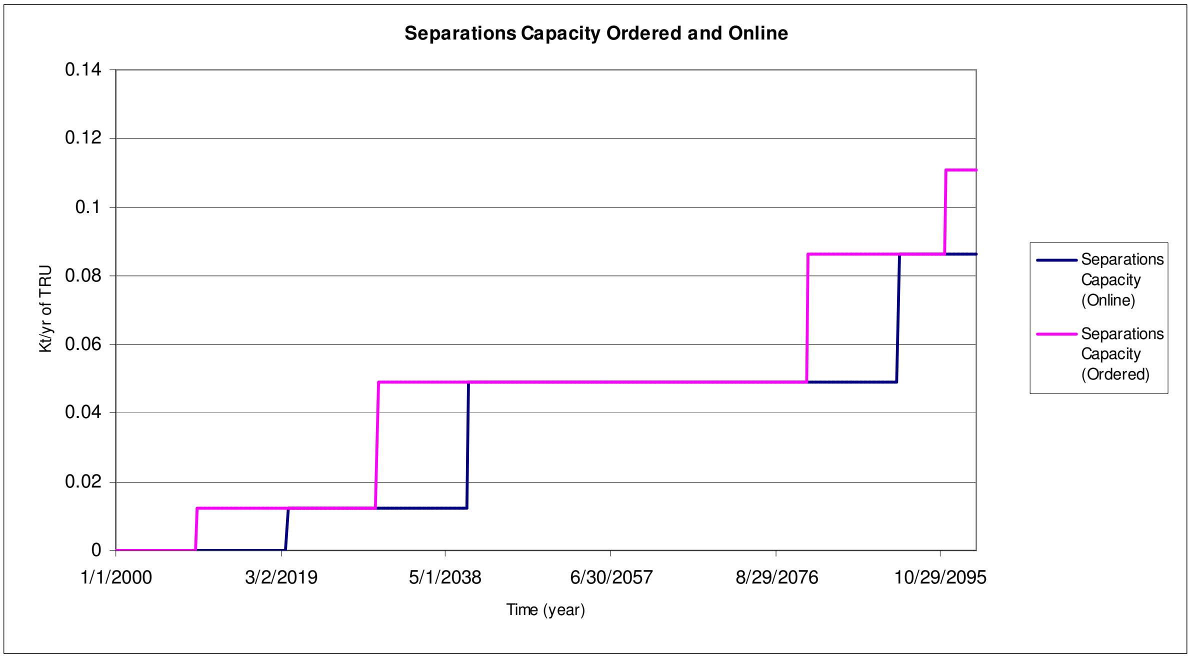

Figure 3-83: Case 4 Separations Capacity with 3 Year Lead Time

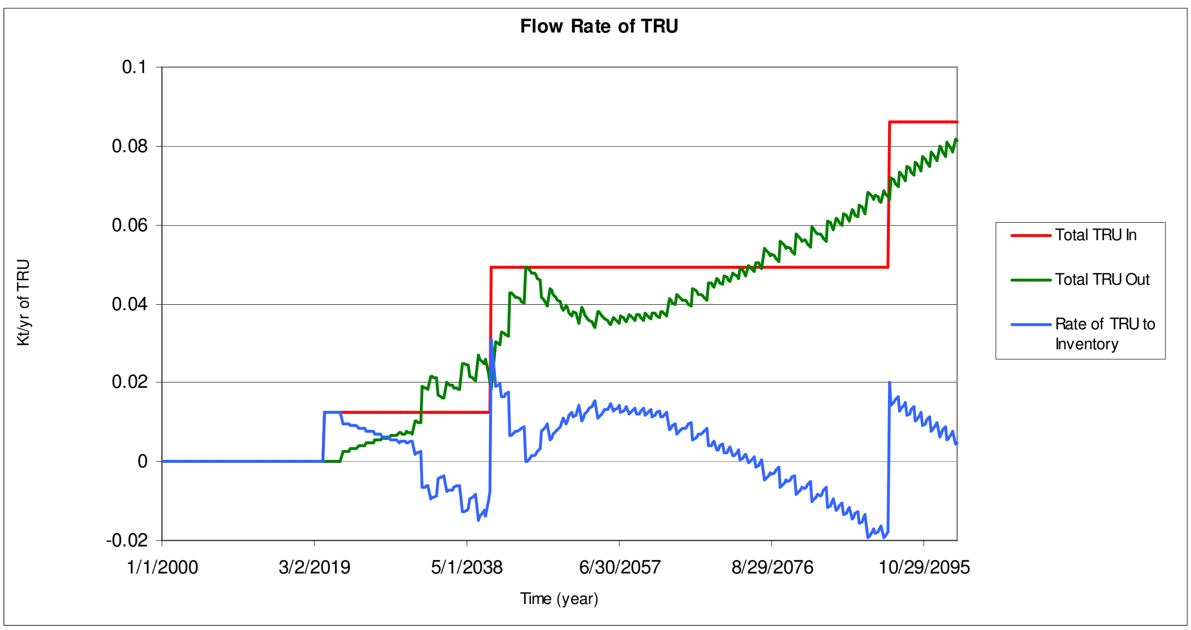

Figure 3-84: Case 4 Flow Rate of TRU to Predicted Inventory with 3 Year Lead Time

Lead Time of 1 Year

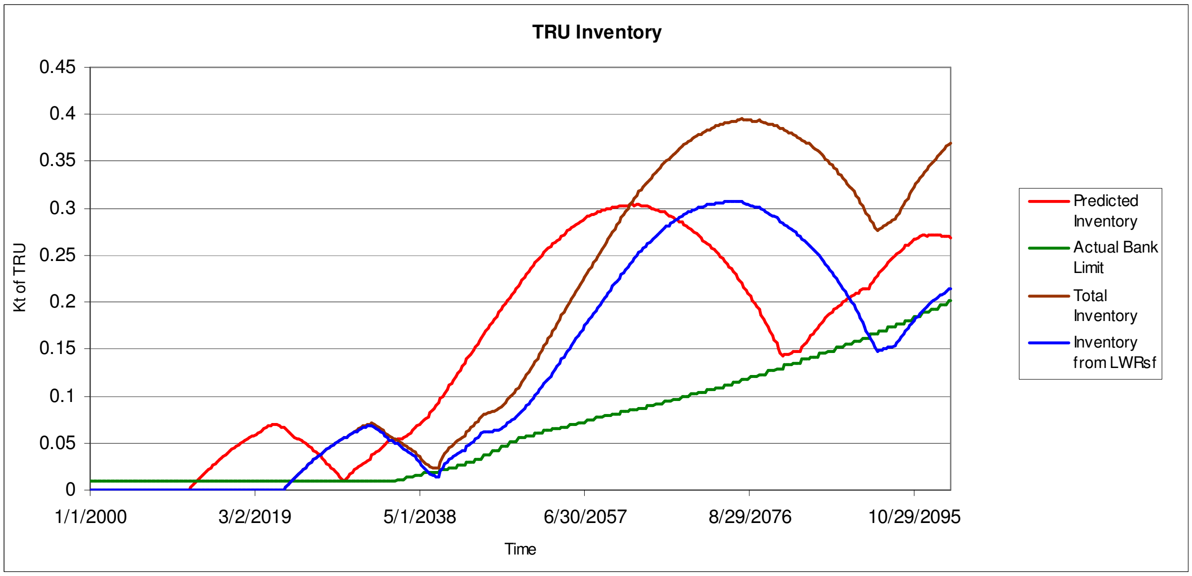

Figure 3-85: Case 4 TRU Inventory with 1 Year Lead Time

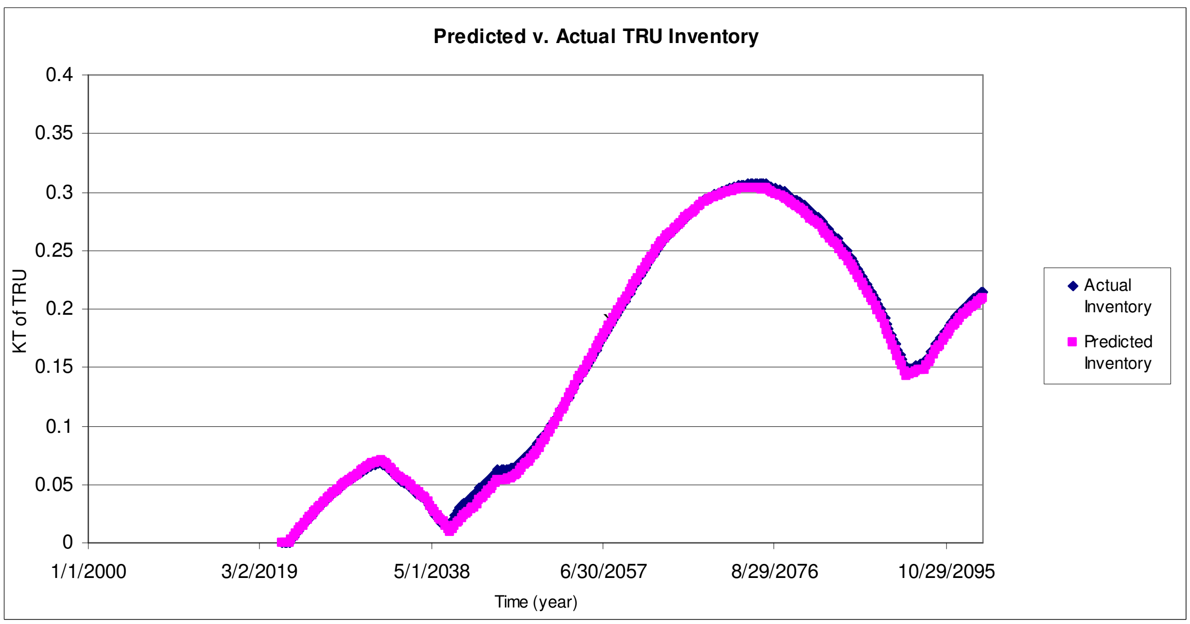

Figure 3-86: Case 4 Predicted v. Actual Inventory with 1 Year Lead Time

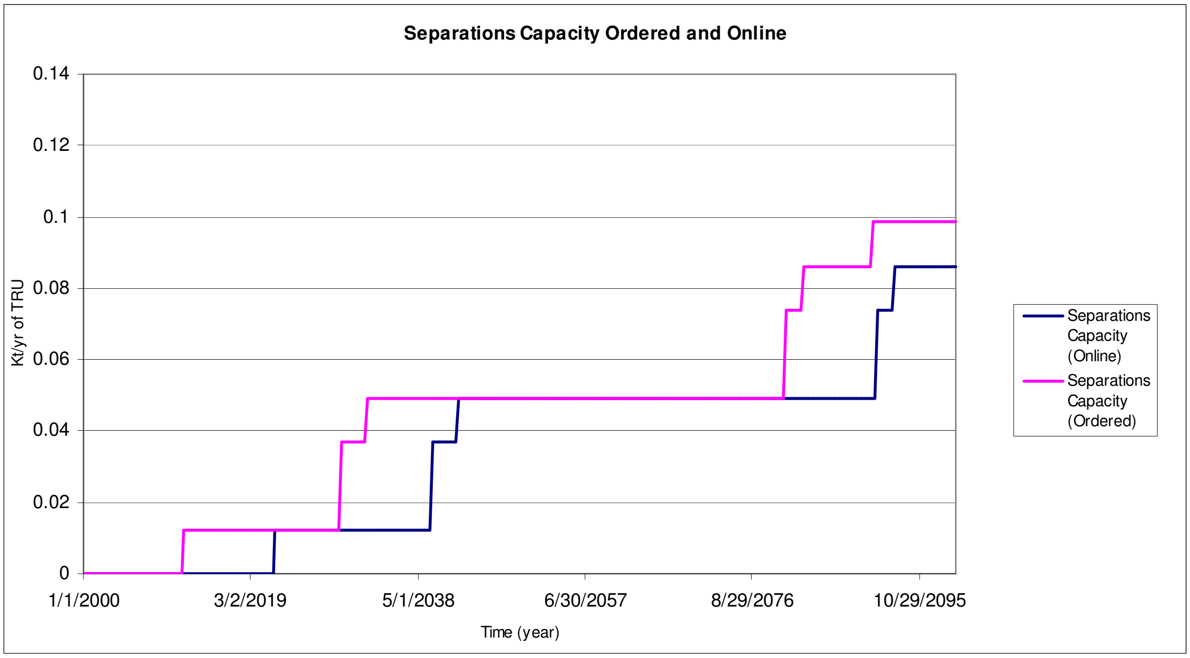

Figure 3-87: Case 4 Separations Capacity (kt/yr) with 1 Year Lead Time

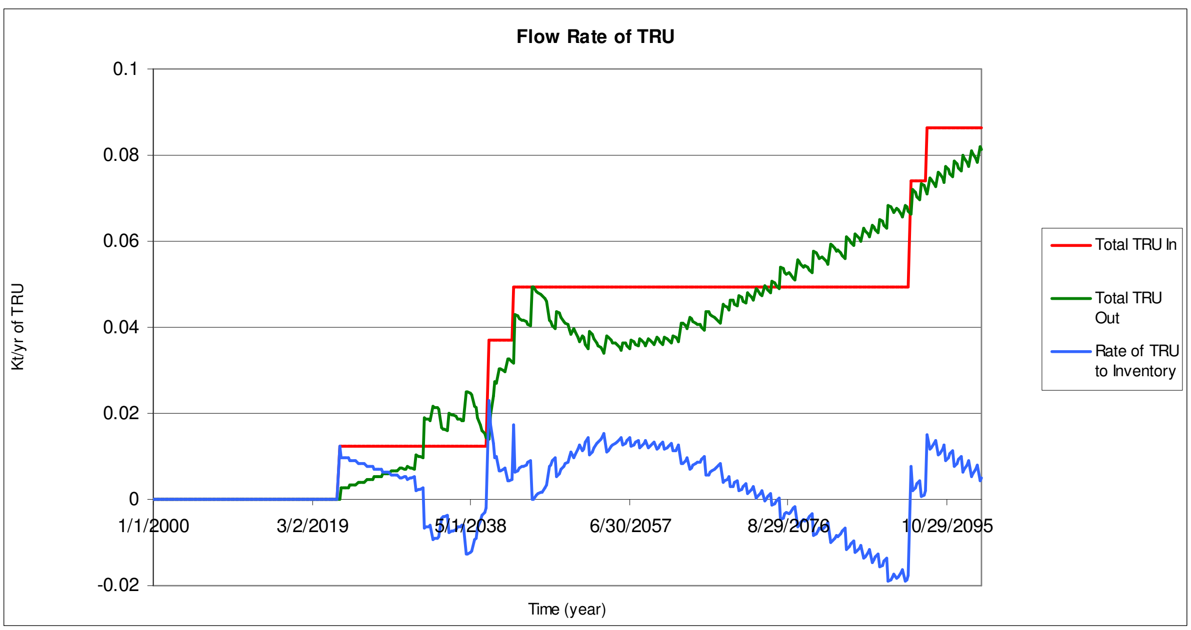

Figure 3-88: Case 4 Flow Rate of TRU to Predicted Inventory with 1 Year Lead Time

3.2.2.2 Case 5 Separation Facility Size of 0.5 Kt/yr

Summary of Case 5

In Case 5 the optimum build scenario with a 0.5Kt/yr separation facility size is with a lead time of 4 years. This gives the system enough time to build up an inventory to meet the demand of new reactors coming online. The inventory is minimum and stays around the minimum bank limit (Figure 3-97). The build rate for this scenario is also spread out nicely with no areas of stagnate growth paired with areas of rapid growth (Figure 3-99).

The results presented in Figure 3-89 - Figure 3-92, Figure 3-93 - Figure 3-96, Figure 3-97 - Figure 3-100, Figure 3-101 - Figure 3-104, and Figure 3-105 - Figure 3-108 show the data for lead times of 7 years, 5 years, 4 years, 3 years and 1 year, respectively.

Lead Time of 7 Years

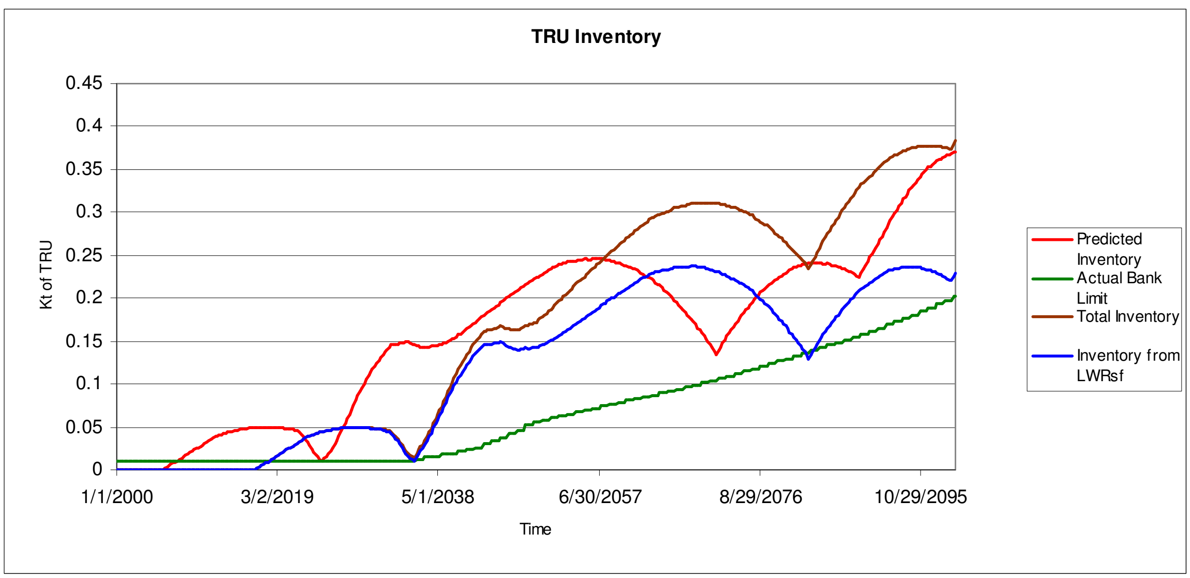

Figure 3-89: Case 5 TRU Inventory with 7 Year Lead Time

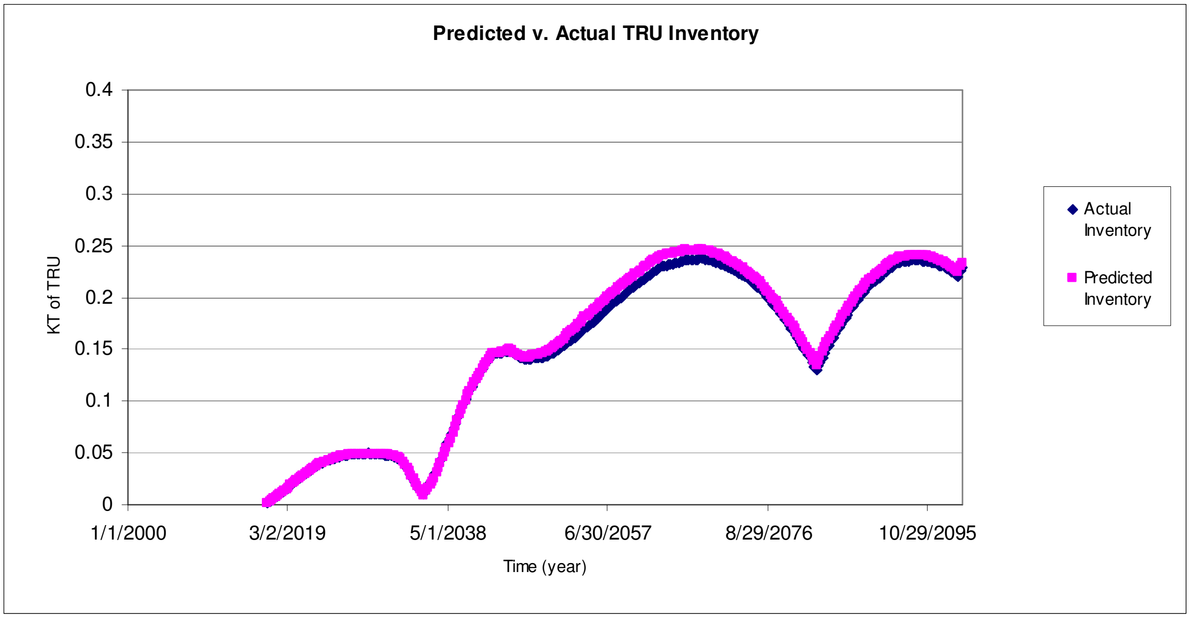

Figure 3-90: Case 5 Predicted v. Actual Inventory with 7 Year Lead Time

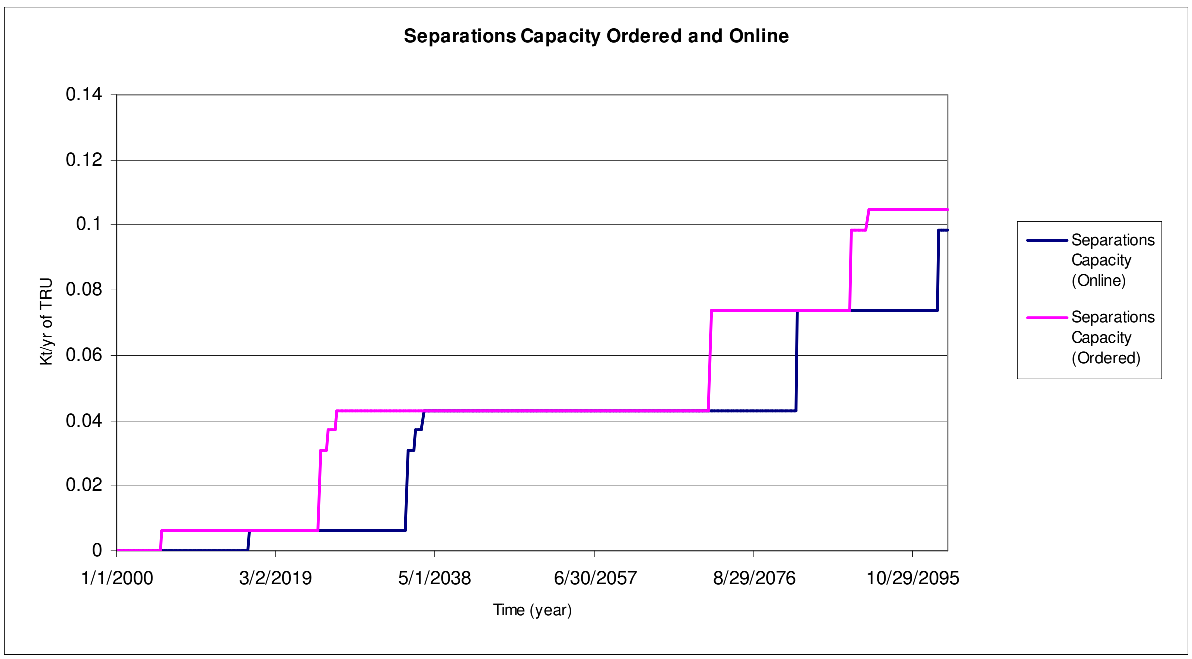

Figure 3-91: Case 5 Separations Capacity (kt/yr) with 7 Year Lead Time

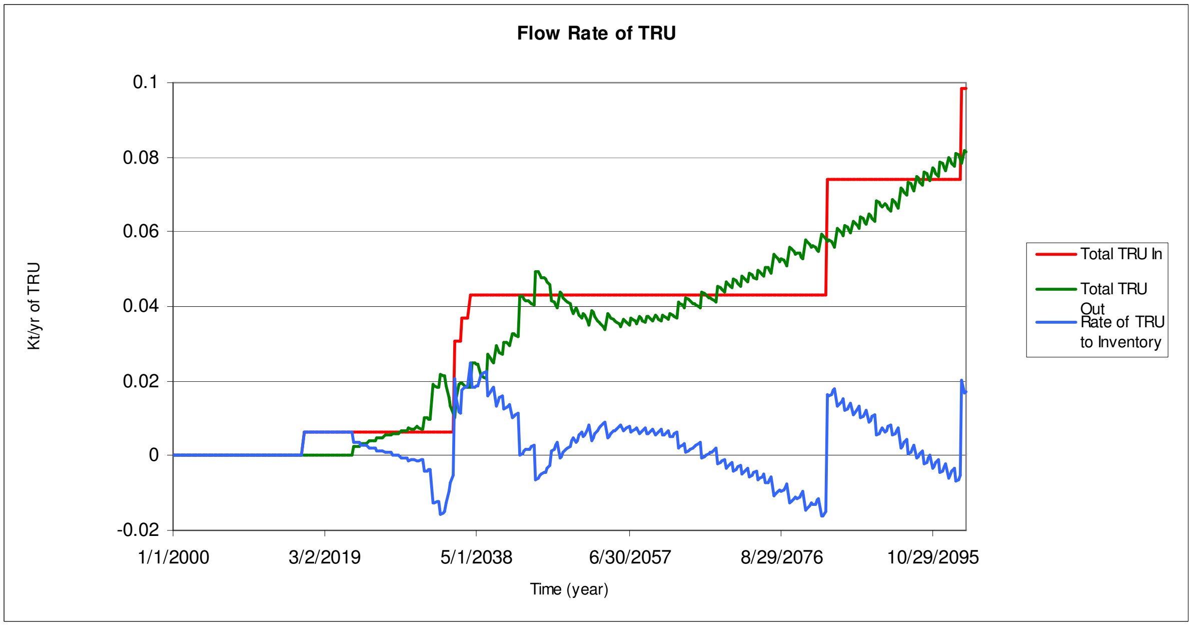

Figure 3-92: Case 5 Flow Rate of TRU to Predicted Inventory with 7 Year Lead Time

<u>Lead Time of 5 Years</u>

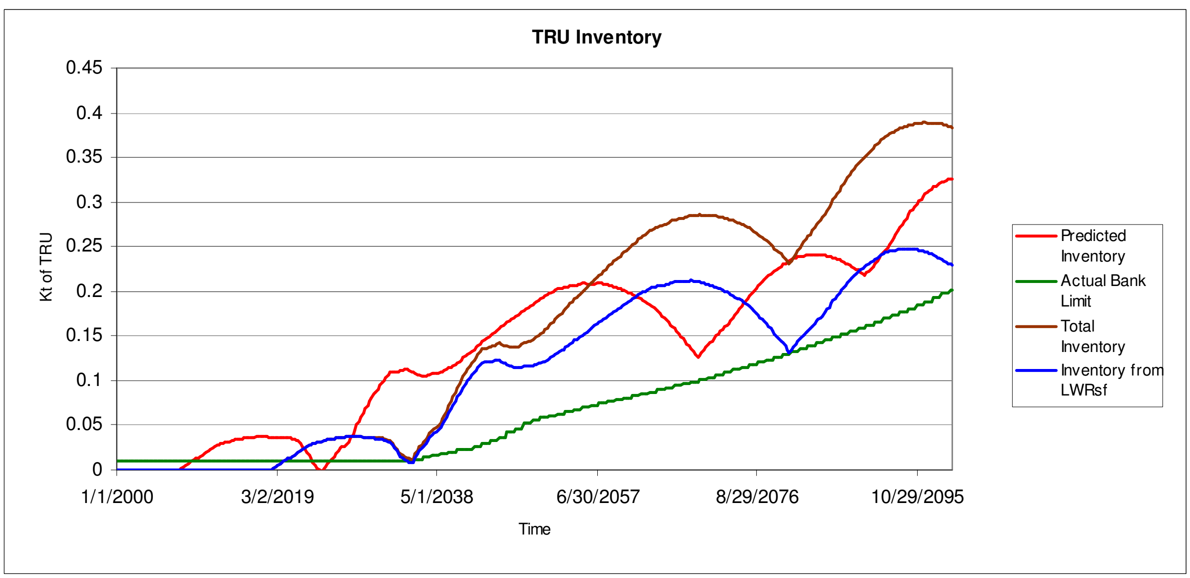

Figure 3-93: Case 5 TRU Inventory with 5 Year Lead Time

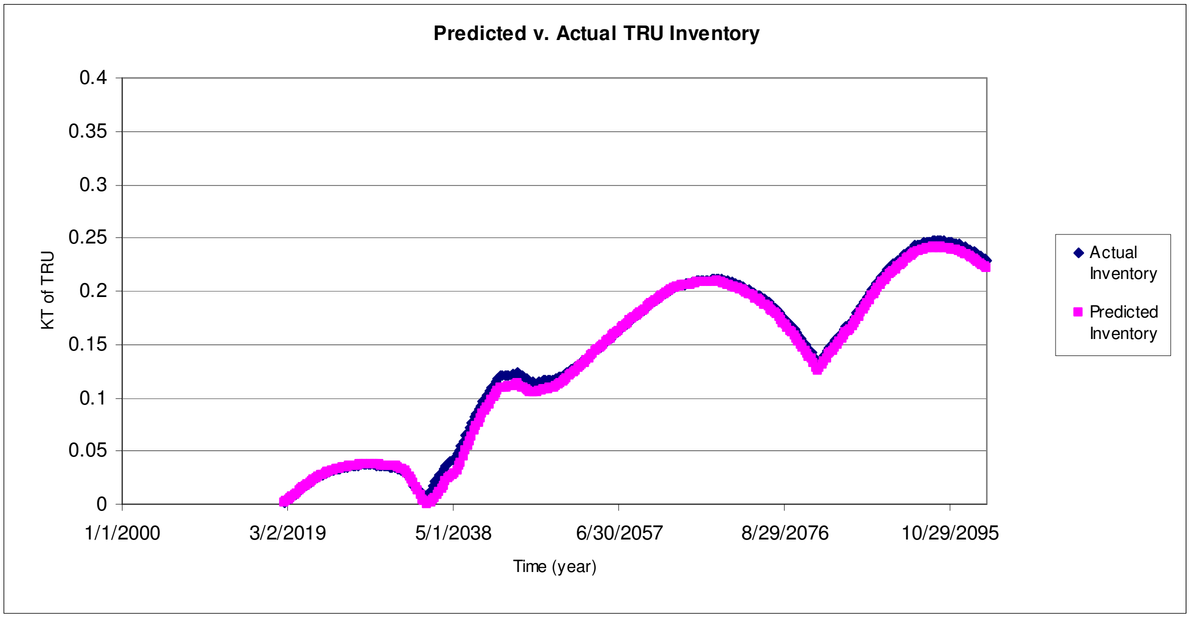

Figure 3-94: Case 5 Predicted v. Actual Inventory with 5 Year Lead Time

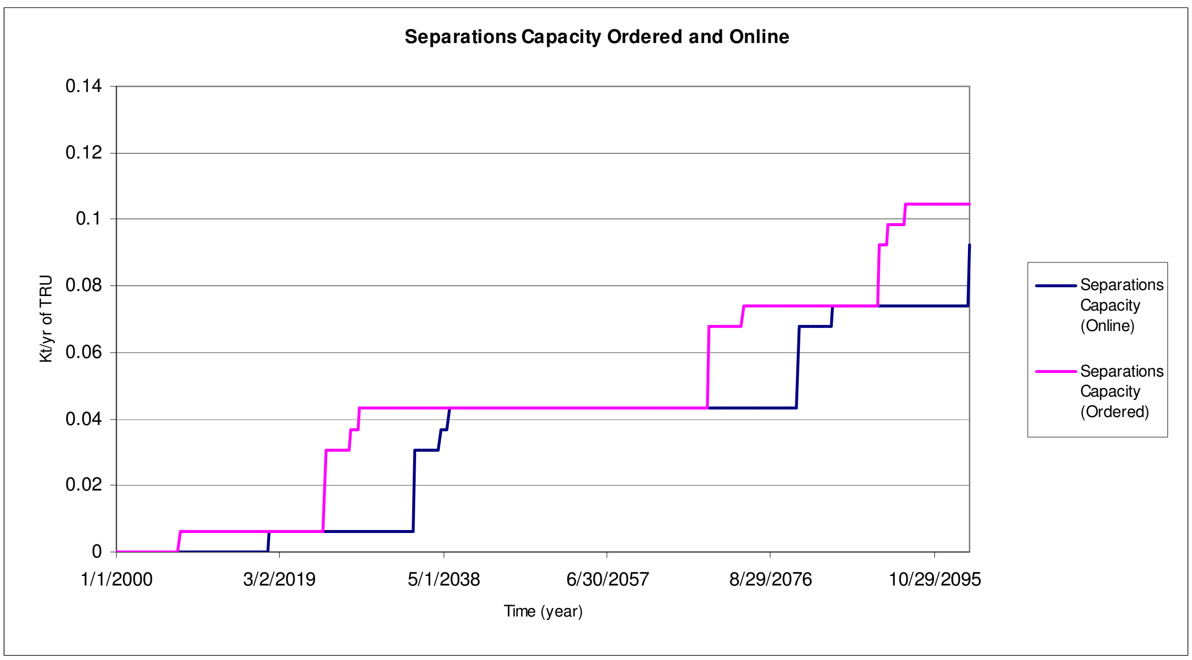

Figure 3-95: Case 5 Separations Capacity (kt/yr) with 5 Year Lead Time

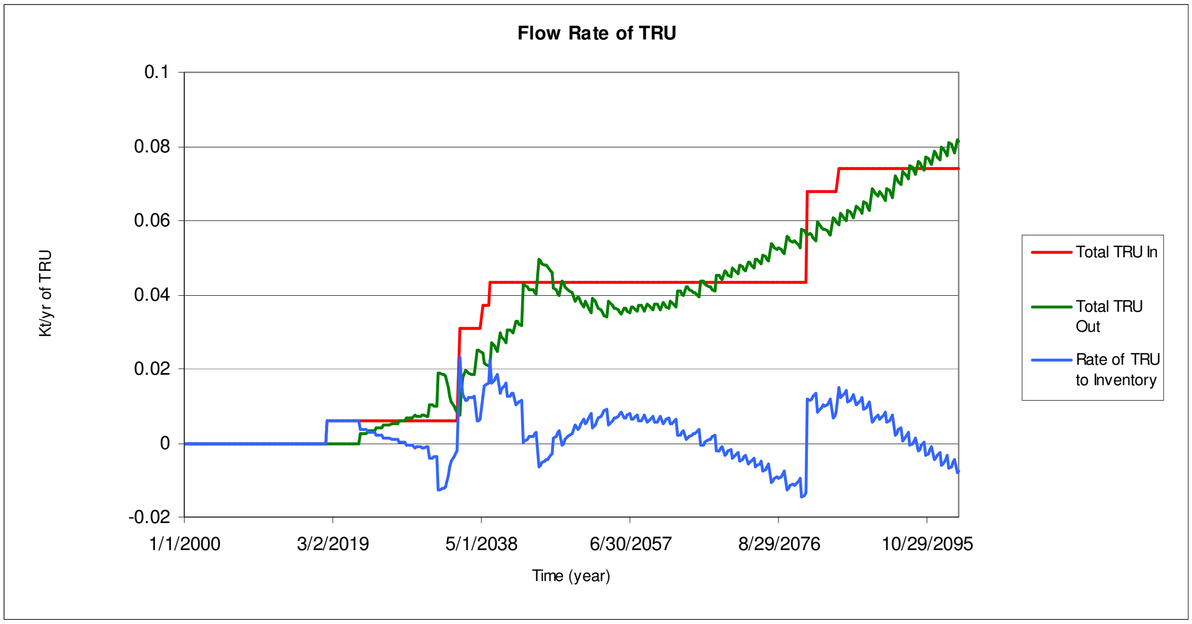

Figure 3-96: Case 5 Flow Rate of TRU to Predicted Inventory with 5 Year Lead Time

Lead Time of 4 Years

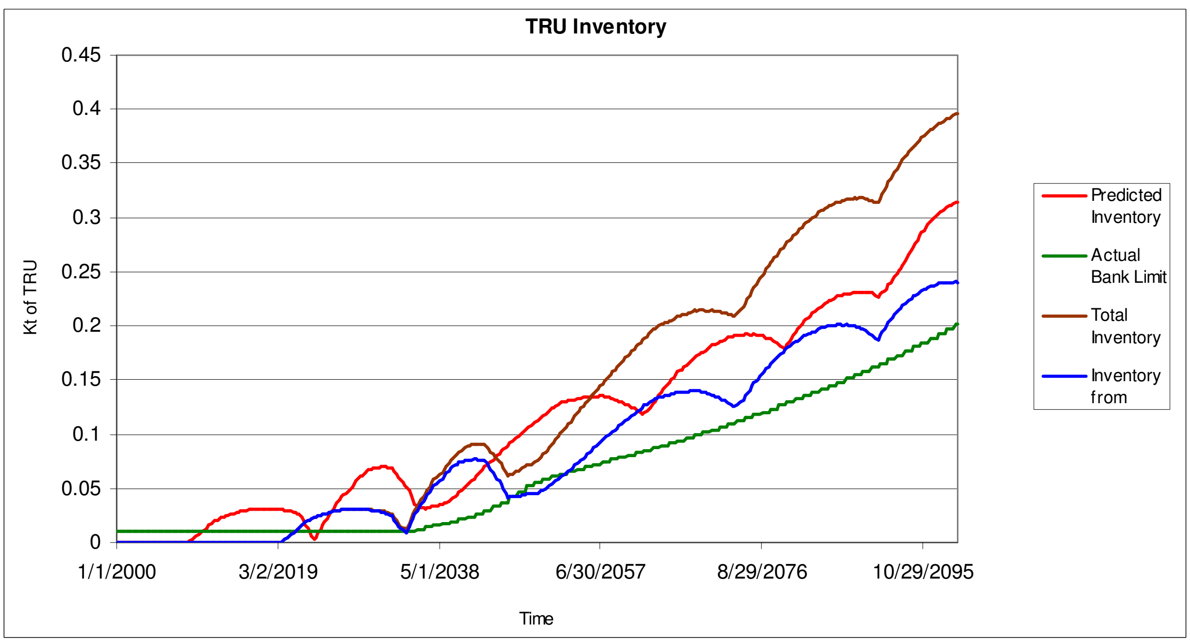

Figure 3-97: Case 5 TRU Inventory with 4 Year Lead Time

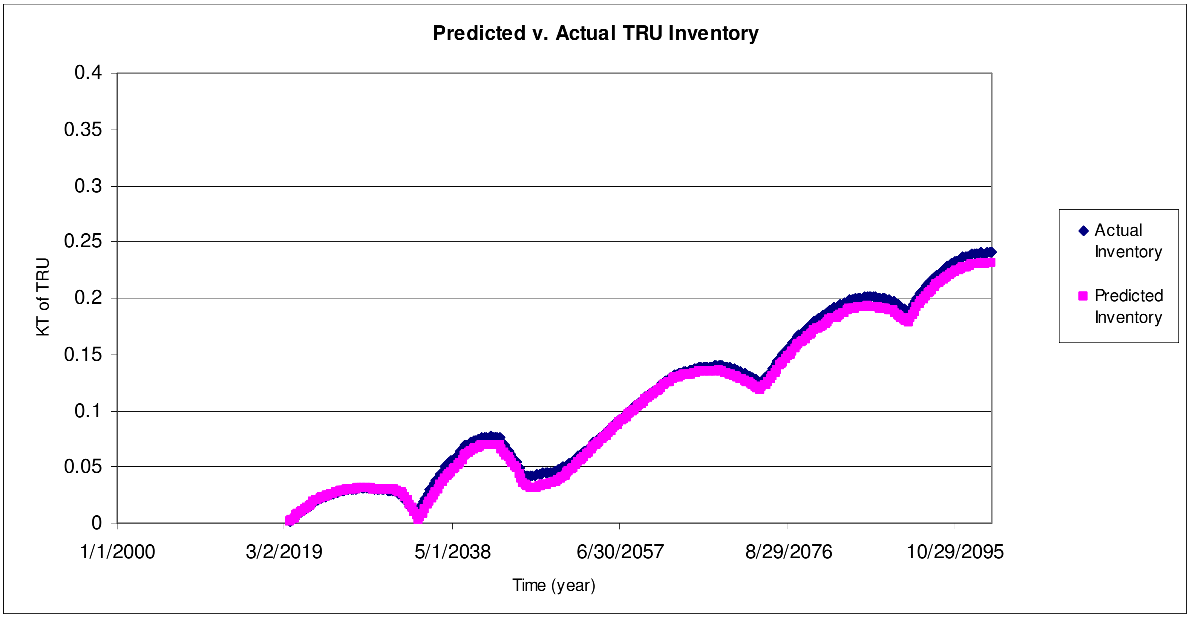

Figure 3-98: Case 5 Predicted v. Actual Inventory with 4 Year Lead Time

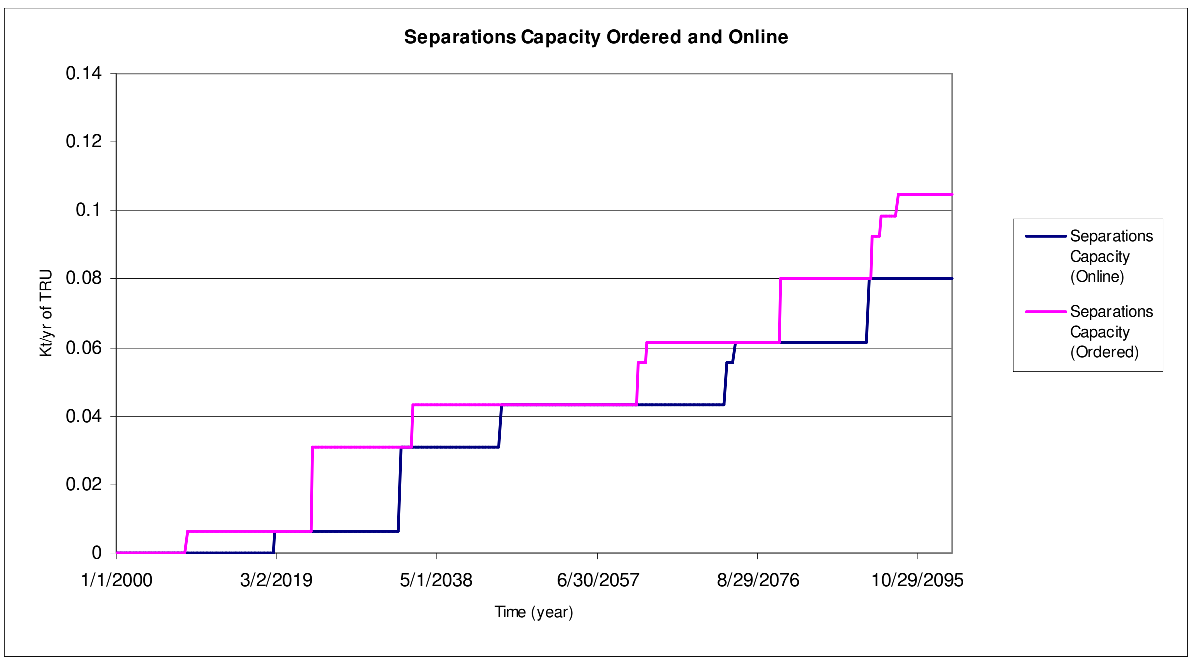

Figure 3-99: Case 5 Separations Capacity (kt/yr) with 4 Year Lead Time

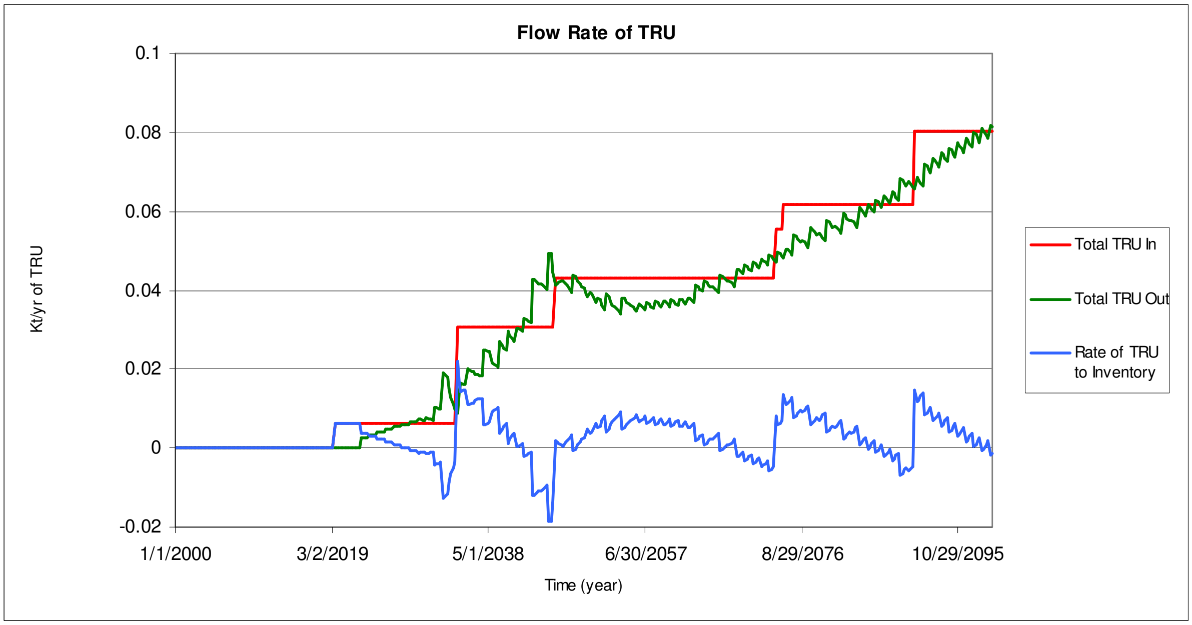

Figure 3-100: Case 5 Flow Rate of TRU to Predicted Inventory with 4 Year Lead Time

Lead Time of 3 Years

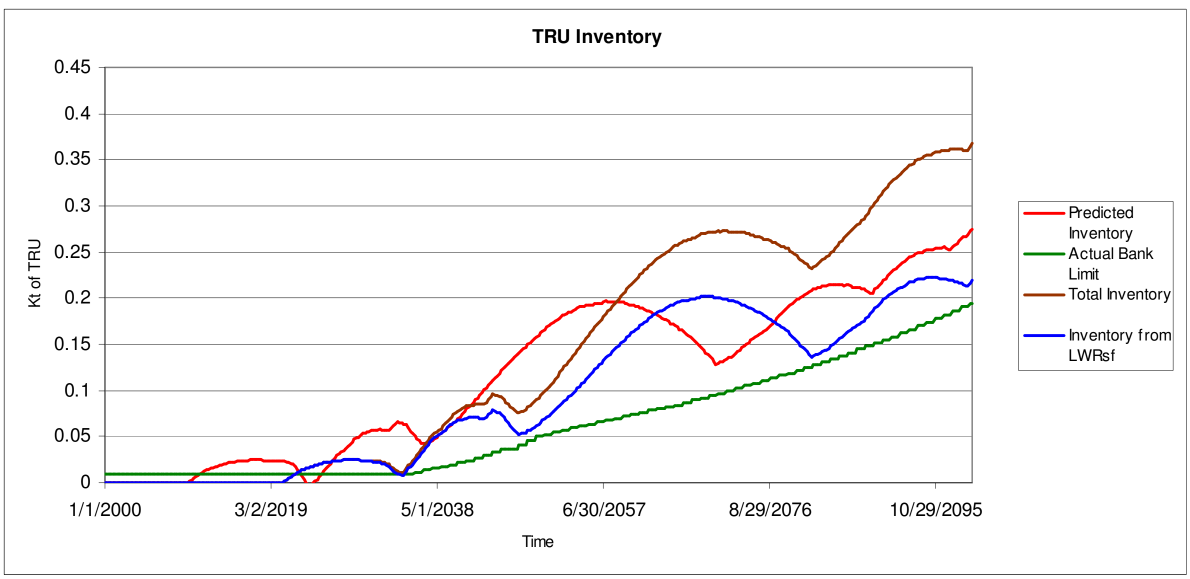

Figure 3-101: Case 5 TRU Inventory with 3 Year Lead Time

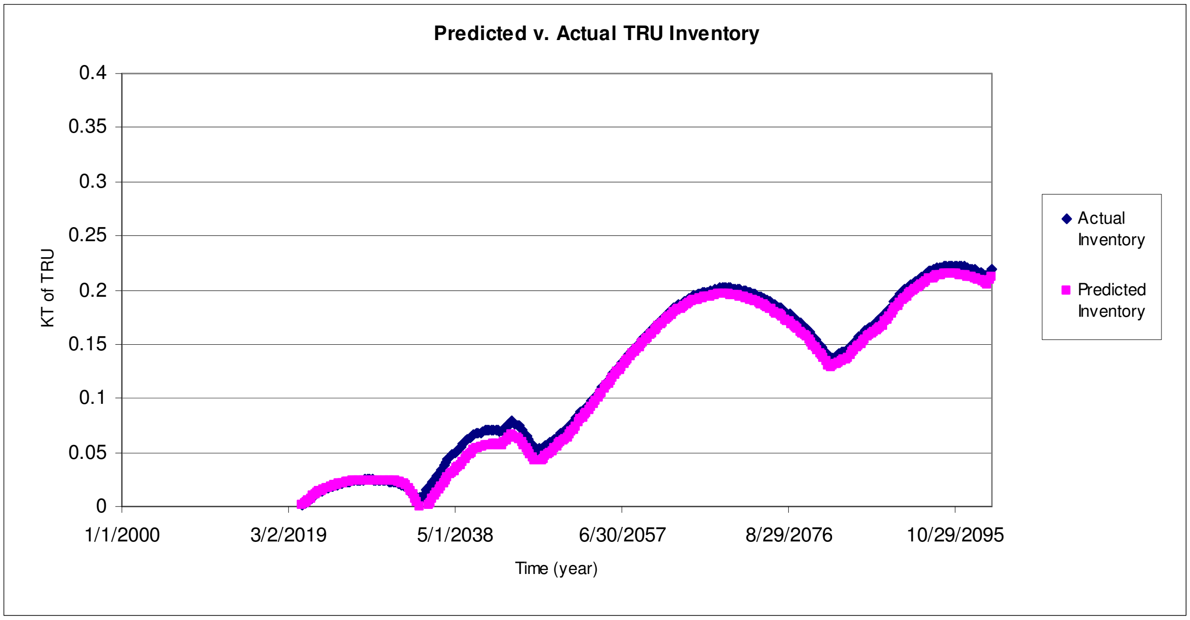

Figure 3-102: Case 5 Predicted v. Actual Inventory with 3 Year Lead Time

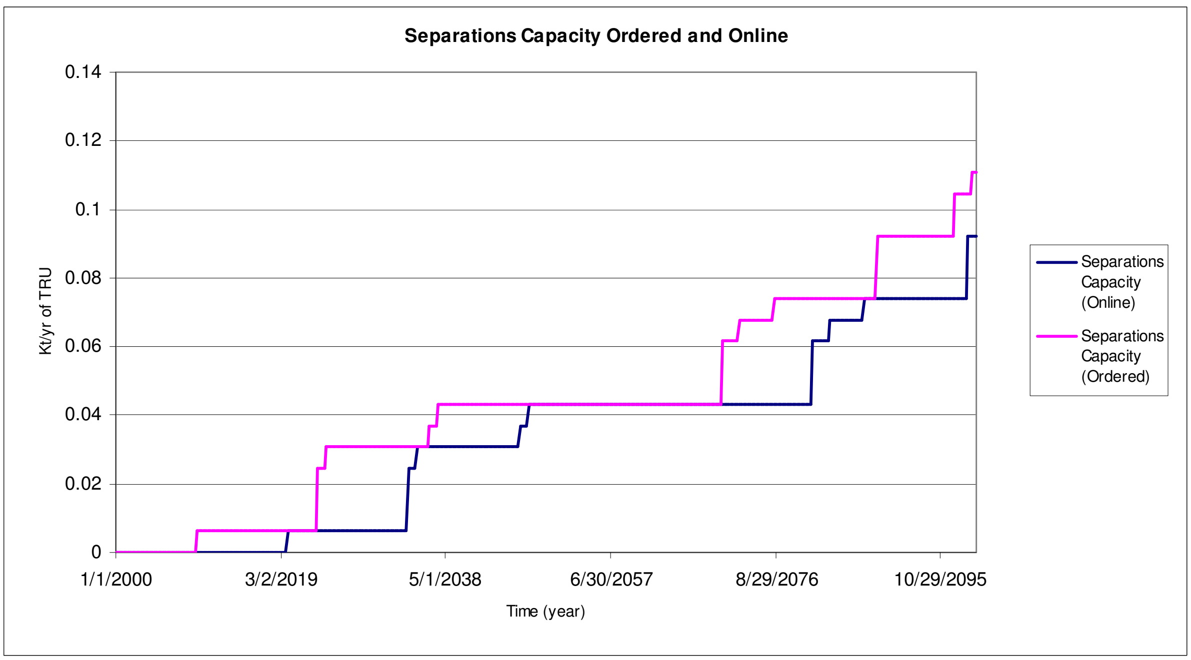

Figure 3-103: Case 5 Separations Capacity (kt/yr) with 3 Year Lead Time

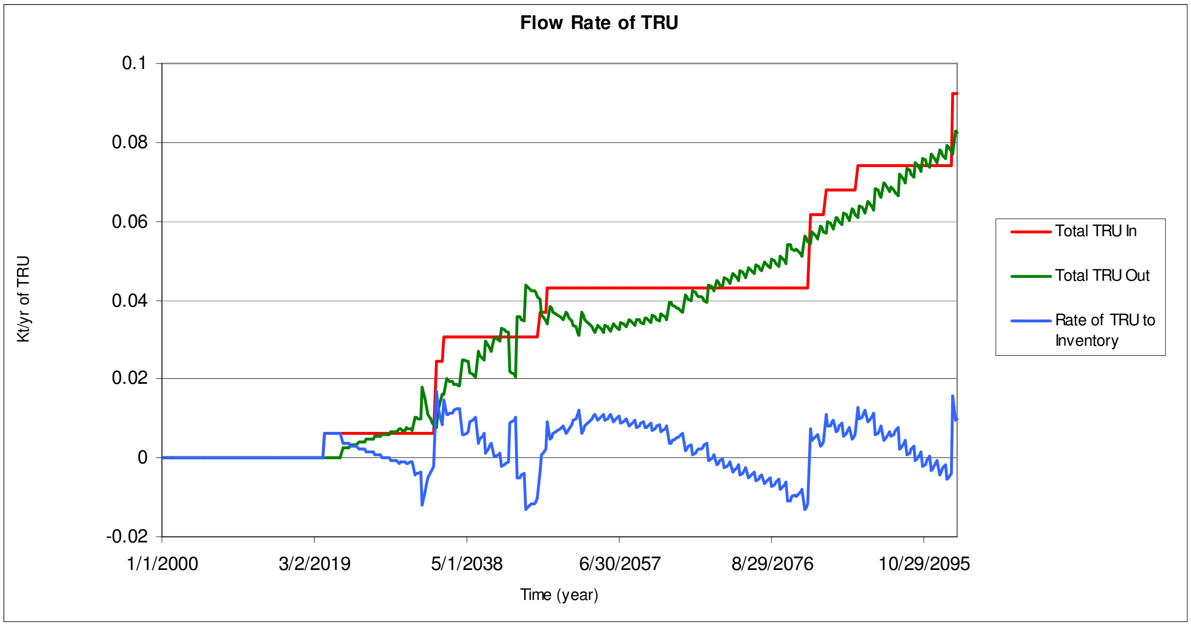

Figure 3-104: Case 5 Flow Rate of TRU to Predicted Inventory with 3 Year Lead Time

<u>Lead Time of 1 Year</u>

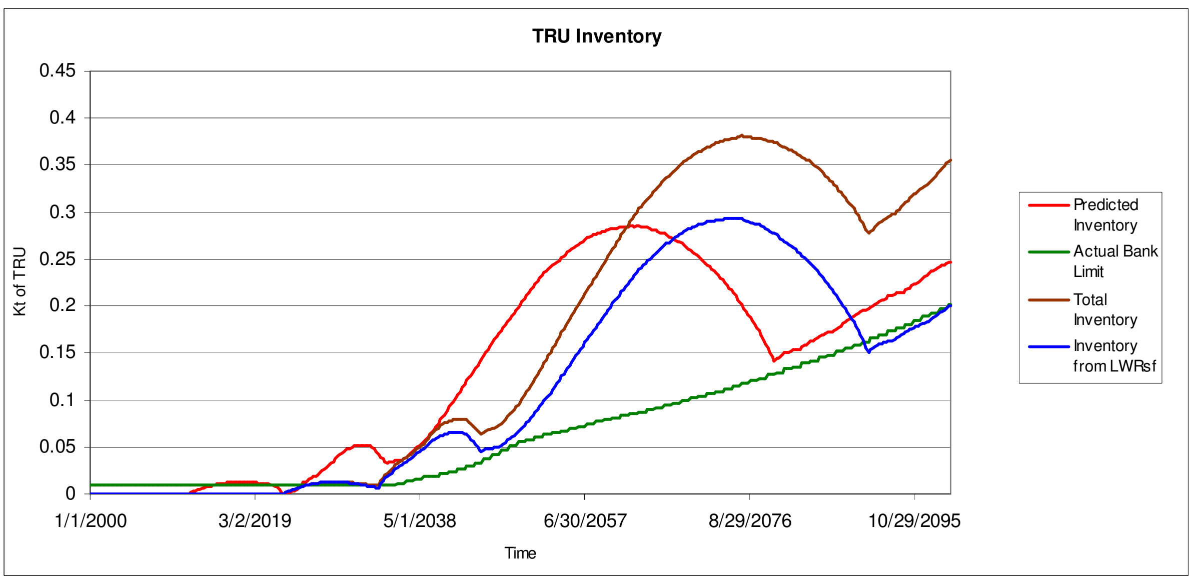

Figure 3-105: Case 5 TRU Inventory with 1 Year Lead Time

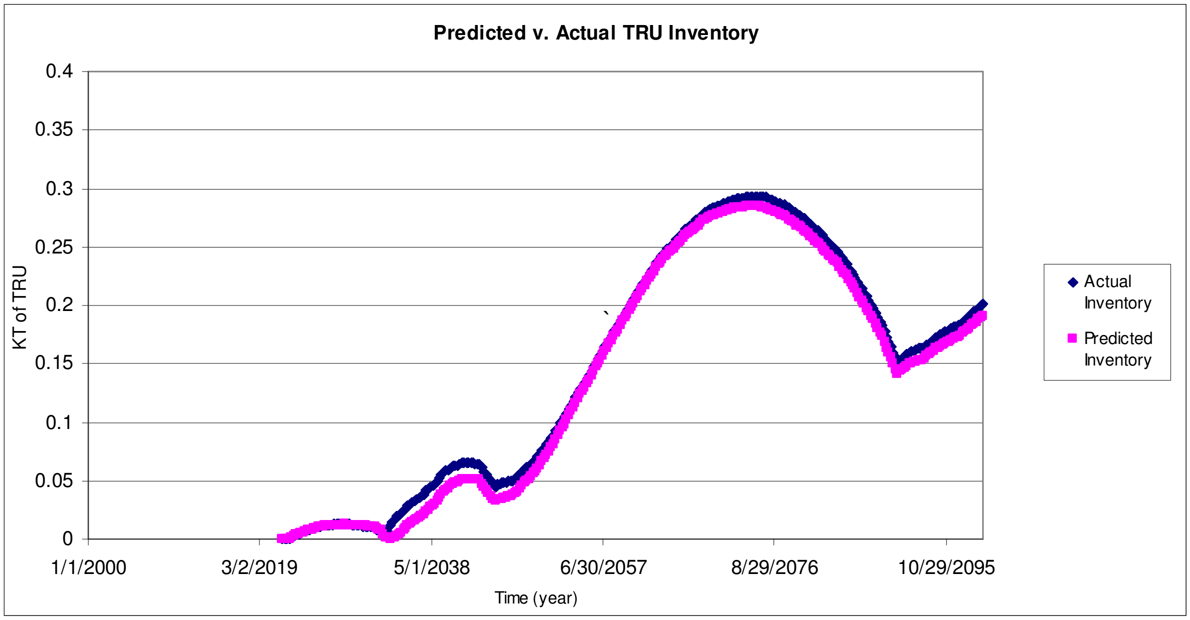

Figure 3-106: Case 5 Predicted v. Actual Inventory with 1 Year Lead Time

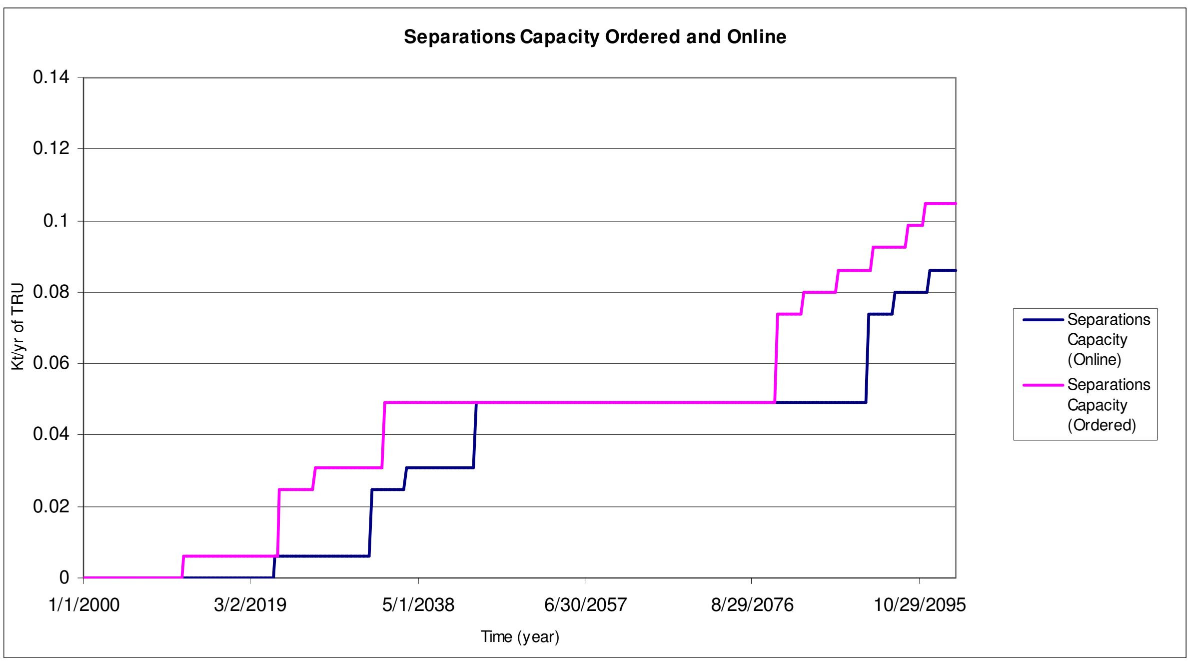

Figure 3-107: Case 5 Separations Capacity with 1 Year Lead Time

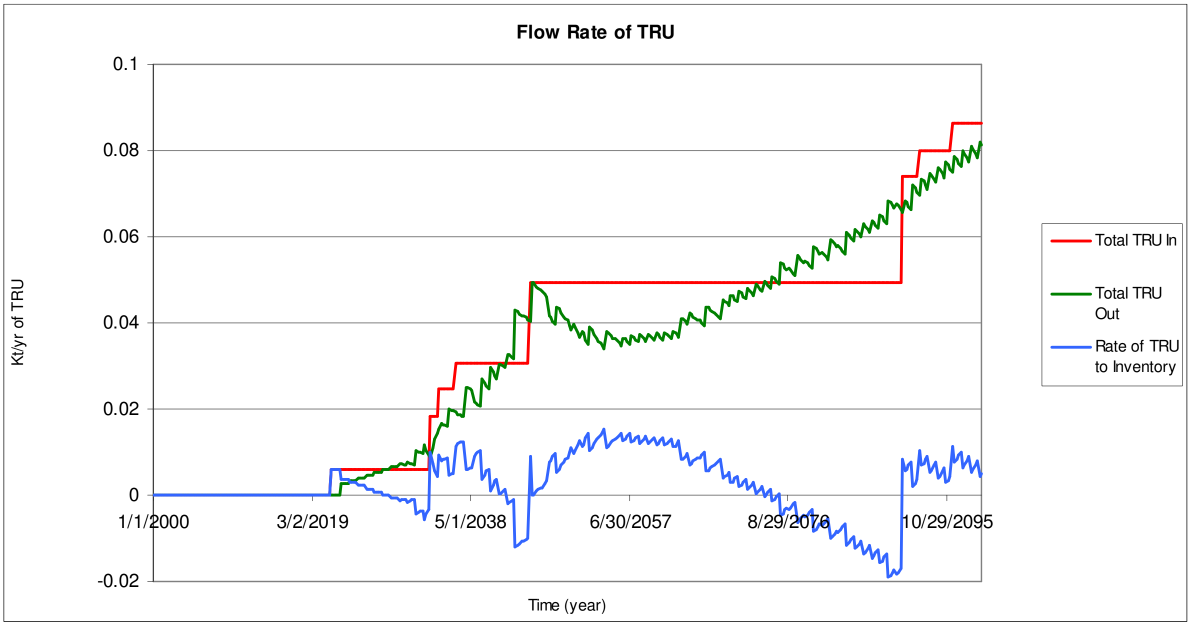

Figure 3-108: Case 5 Flow Rate of TRU to Predicted Inventory with 1 Year Lead Time

3.2.2.3 Case 6 Separation Facility Size of 0.25 Kt/yr

Summary of Case 6

The most optimum scenario within Case 6 is with a lead time of 5 years. This produces a steady production of separations capacity (Figure 3-115) with a TRU inventory that hovers around the minimum bank limit (Figure 3-113). The other scenarios have higher TRU inventories and large separation capacity build rates paired with stagnate build rates.

The results presented in Figure 3-109 - Figure 3-112, Figure 3-113 - Figure 3-116, Figure 3-117 - Figure 3-120, Figure 3-121 - Figure 3-124, and Figure 3-125 - Figure 3-128 show the results for the lead times of 7 years, 5 years, 4 years, 3 years, and 1 year, respectively.

Lead Time of 7 Years

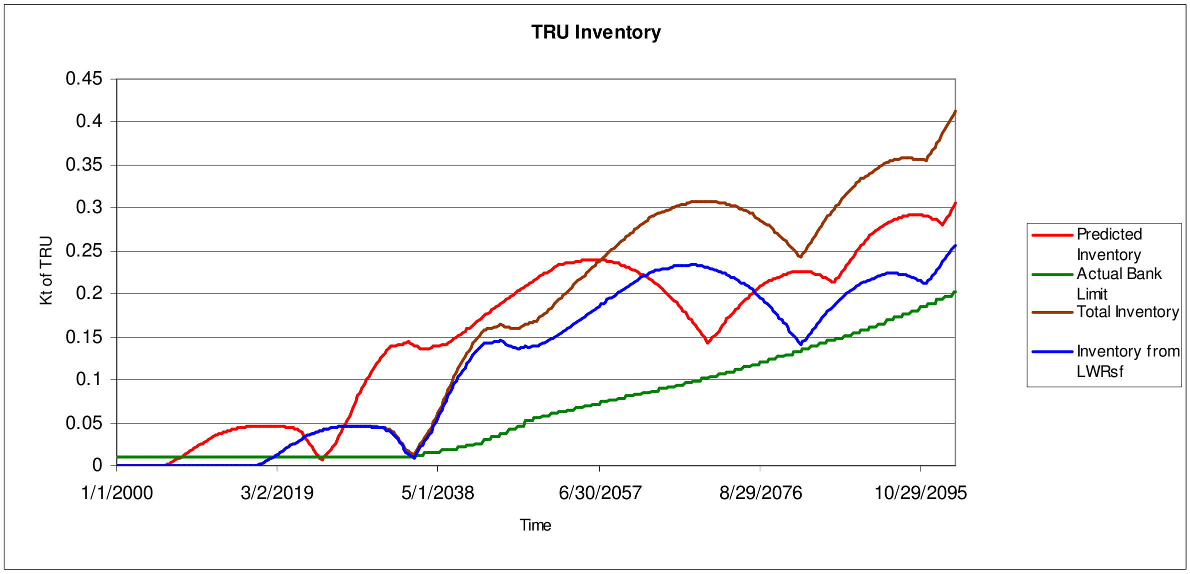

Figure 3-109: Case 6 TRU Inventory with 7 Year Lead Time

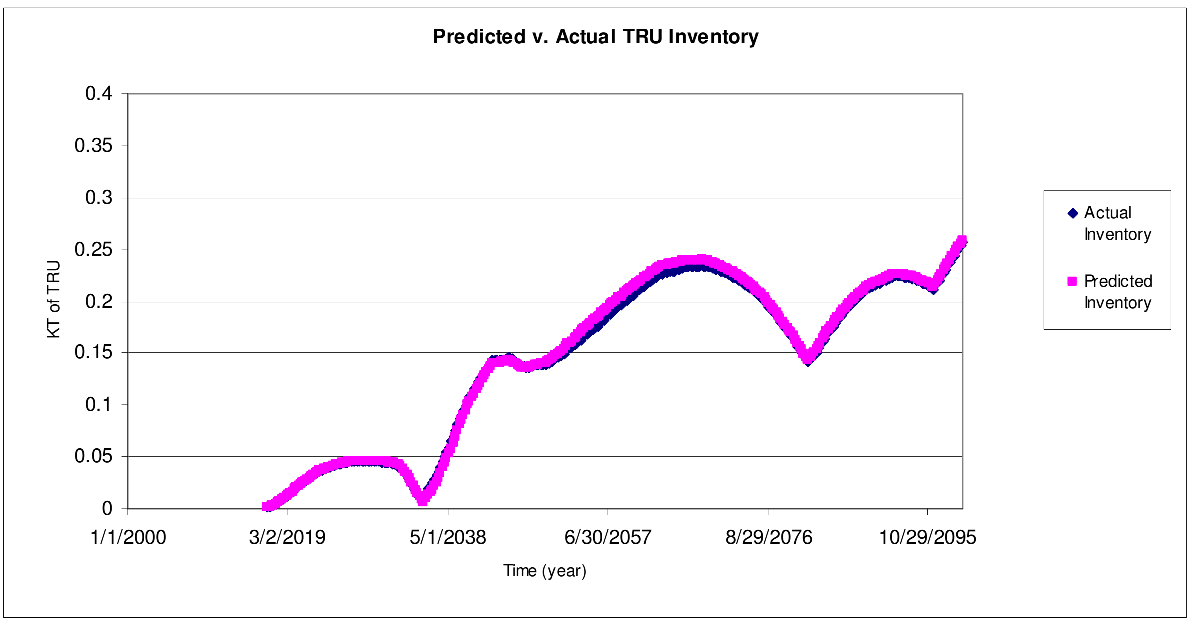

Figure 3-110: Case 6 Predicted v. Actual Inventory with Lead Time of 7 Years

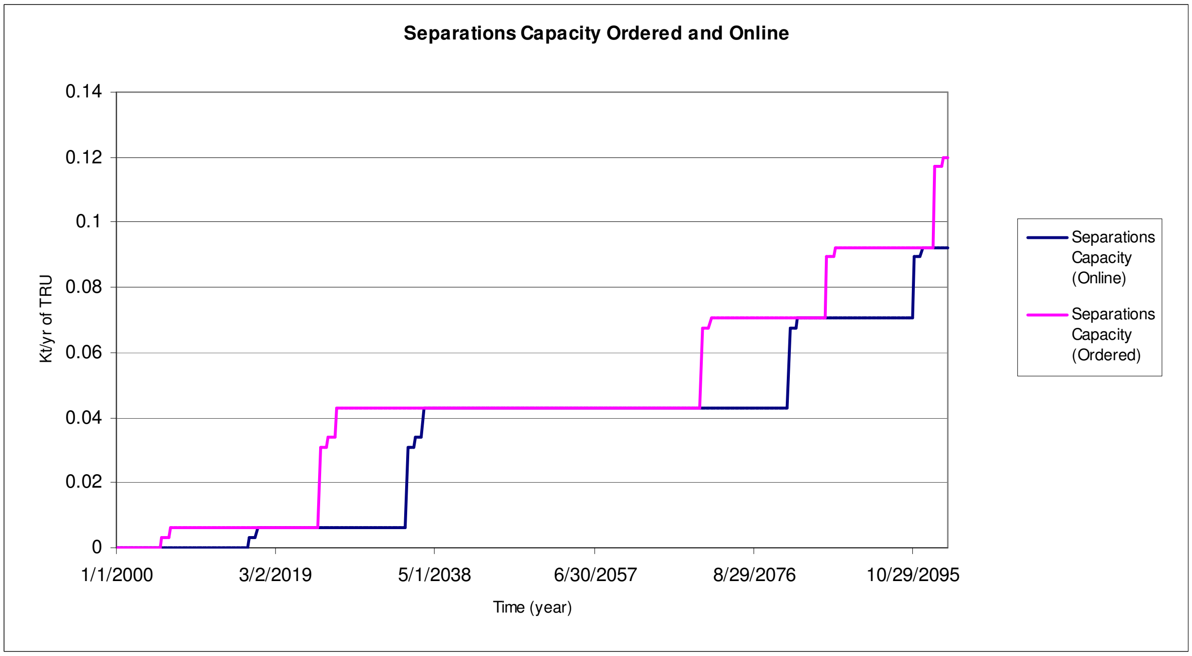

Figure 3-111: Case 6 Separations Capacity (kt/yr) with 7 Year Lead Time

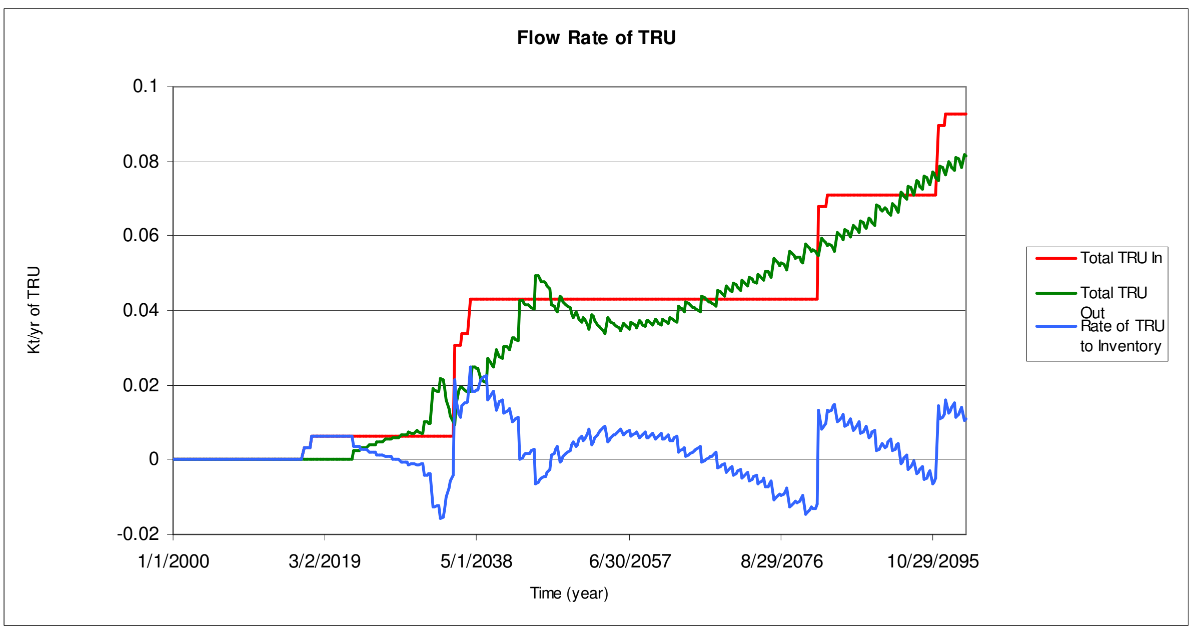

Figure 3-112: Case 6 Flow Rate of TRU to Predicted Inventory with Lead Time of 7 Years

Lead Time of 5 Years

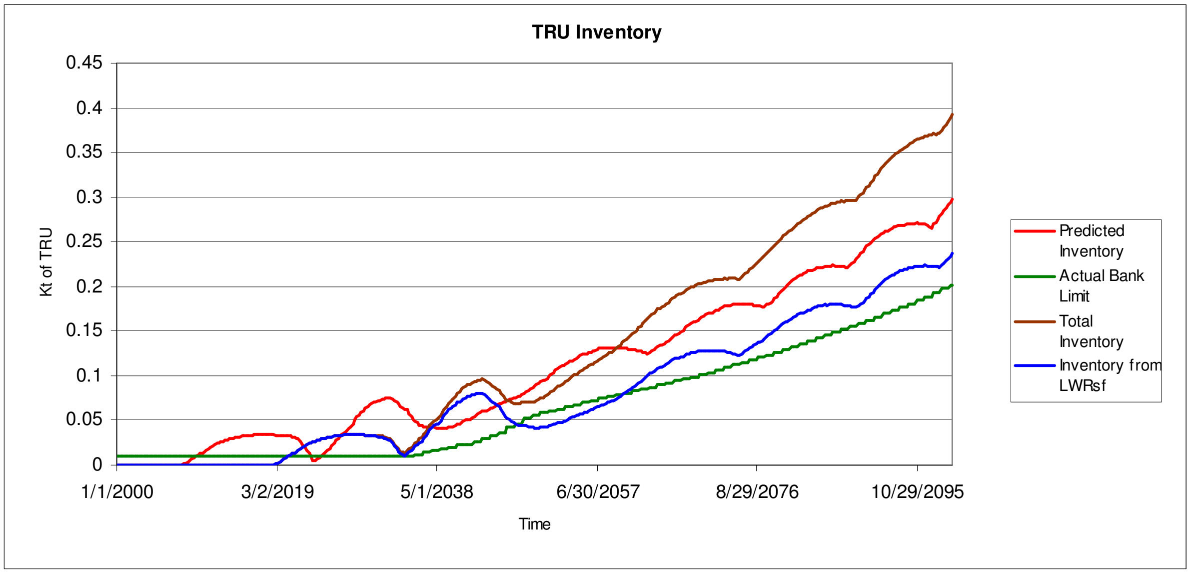

Figure 3-113: Case 6 TRU Inventory with 5 Year Lead Time

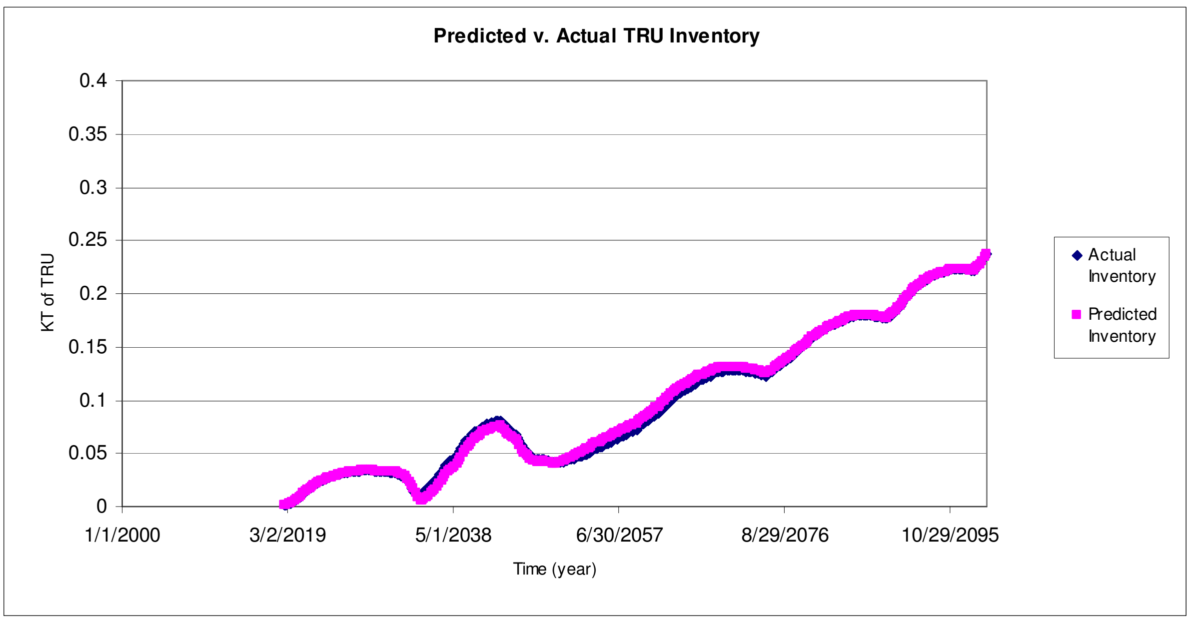

Figure 3-114: Case 6 Predicted v. Actual Inventory with 5 Year Lead Time

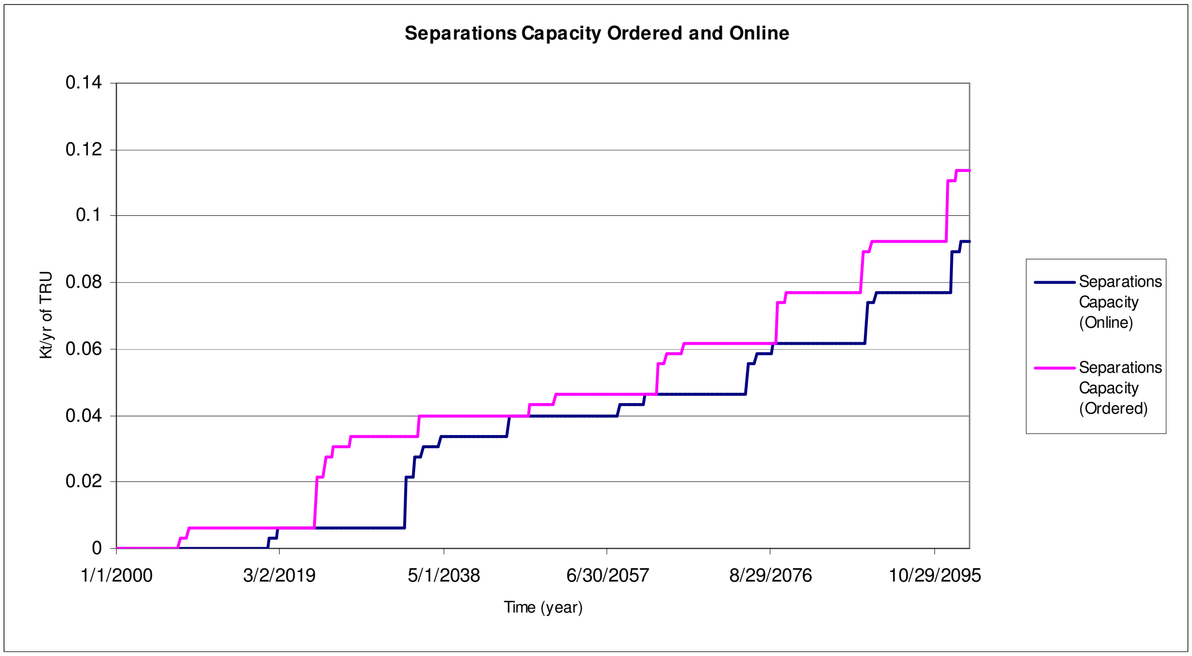

Figure 3-115: Case 6 Separations Capacity (kt/yr) with 5 Year Lead Time

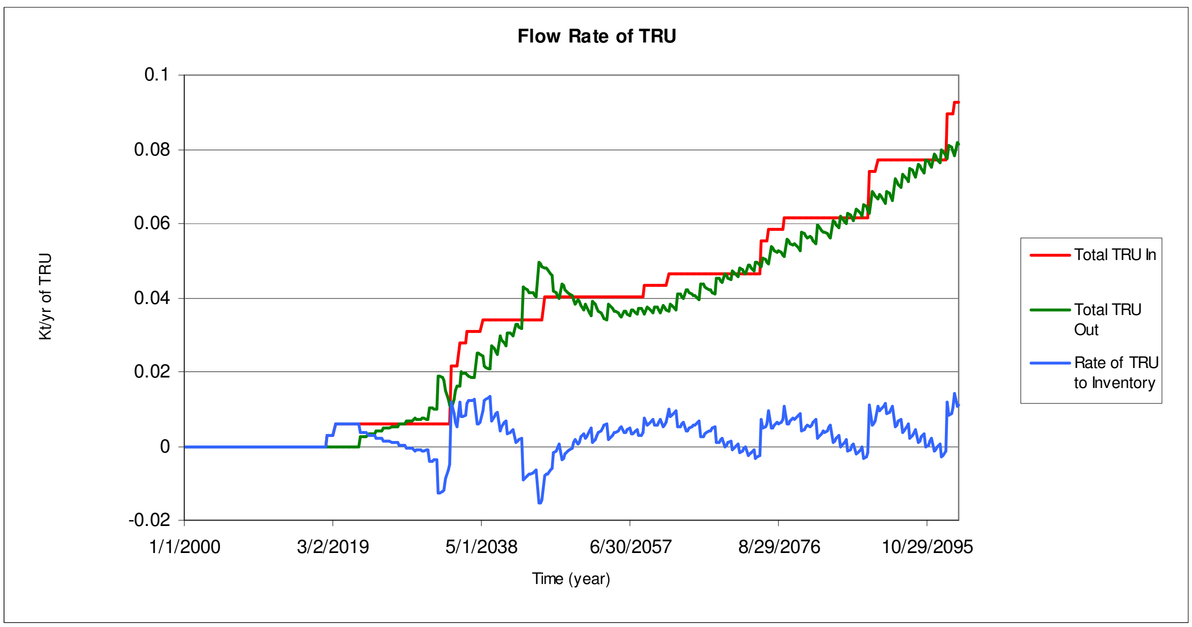

Figure 3-116: Case 6 Flow Rate of TRU to Predicted Inventory with 5 Year Lead Time

Lead Time of 4 Years

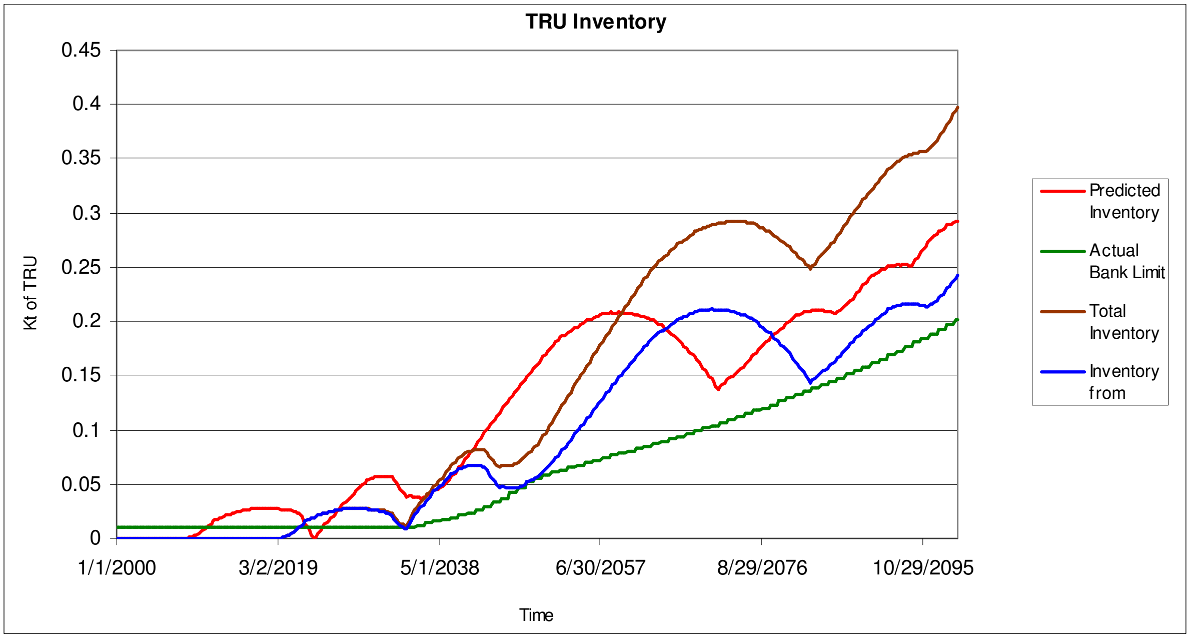

Figure 3-117: Case 6 TRU Inventory with 4 Year Lead Time

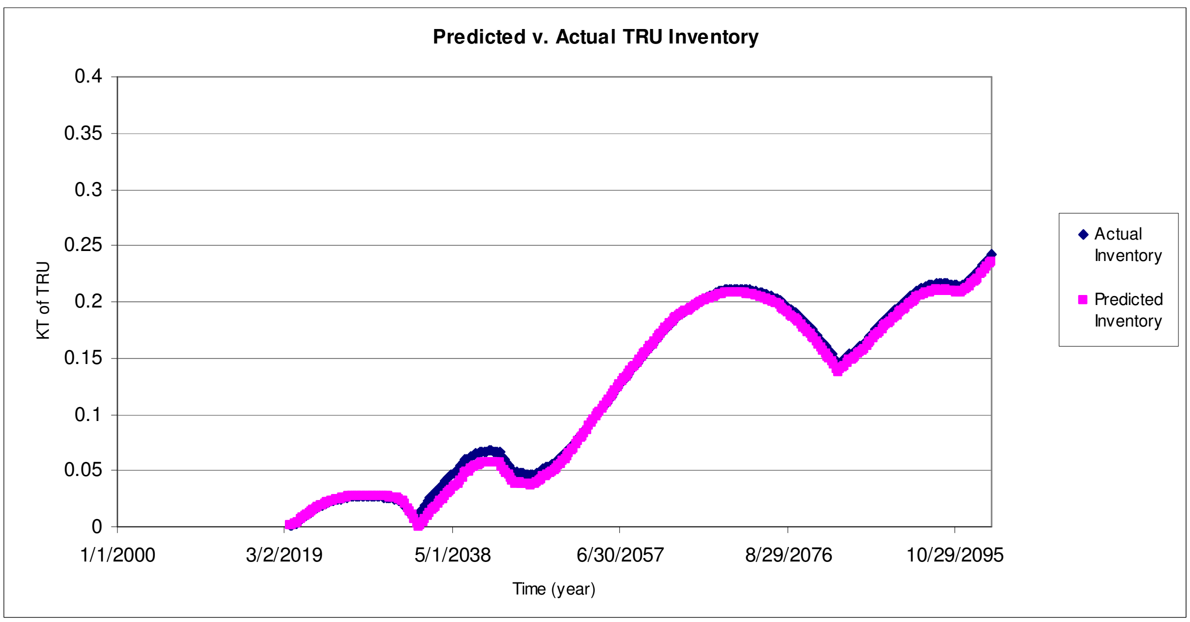

Figure 3-118: Case 6 Predicted v. Actual Inventory with 4 Year Lead Time

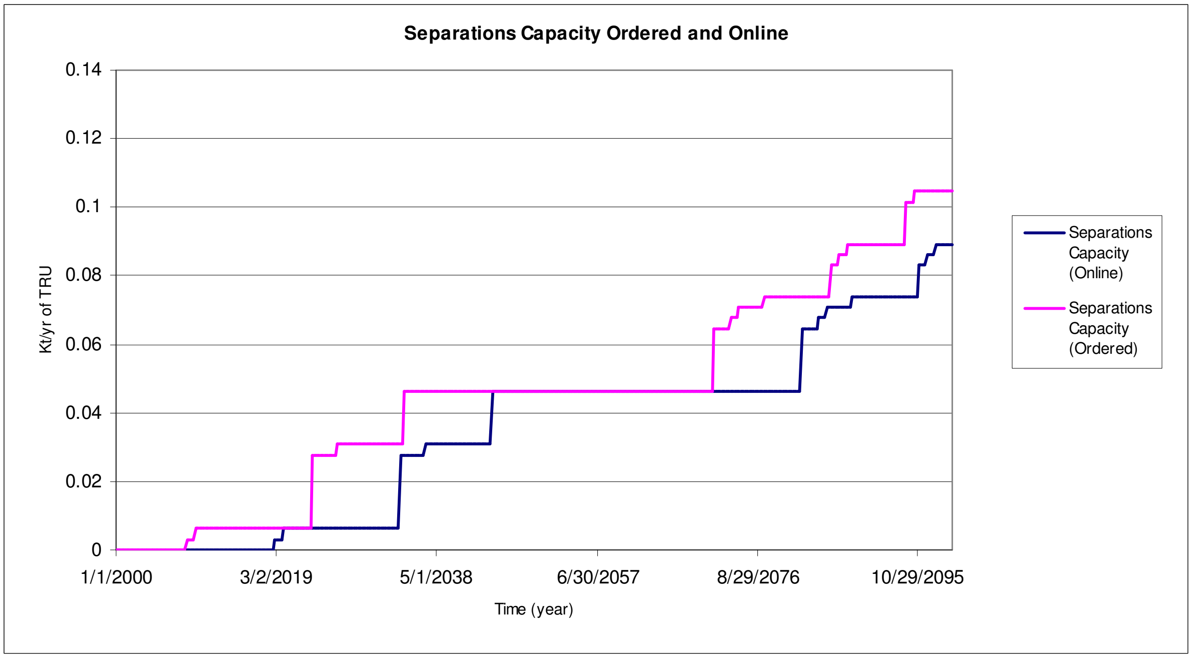

Figure 3-119: Case 6 Separations Capacity (kt/yr) with 4 Year Lead Time

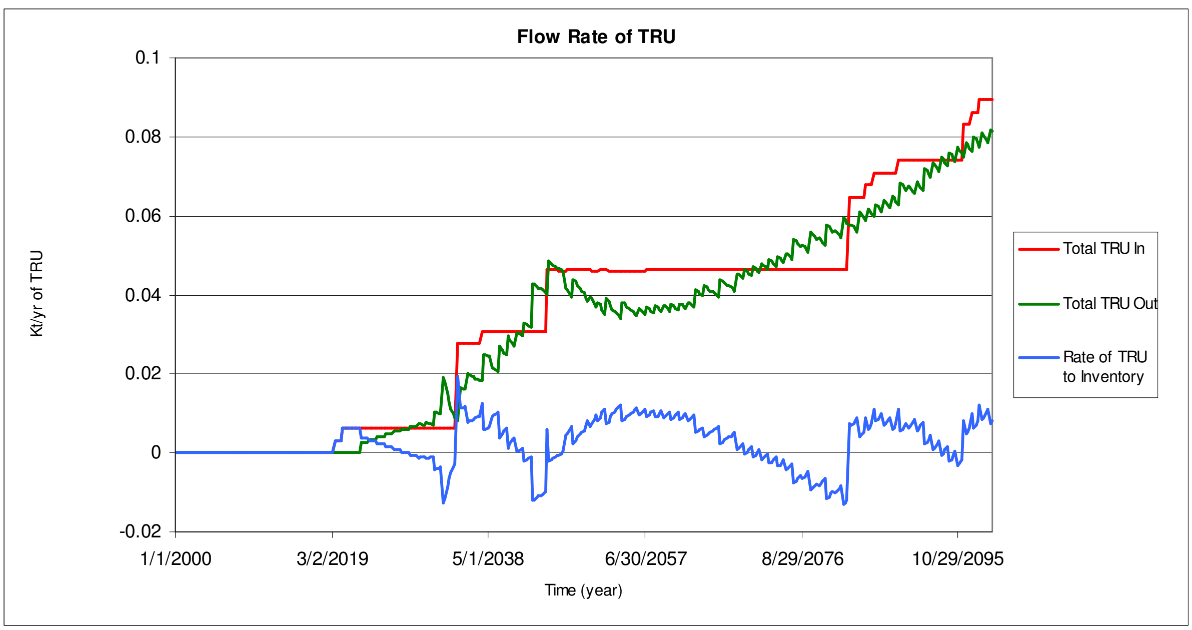

Figure 3-120: Case 6 Flow Rate of TRU to Predicted Inventory with 4 Year Lead Time

Lead Time of 3 Years

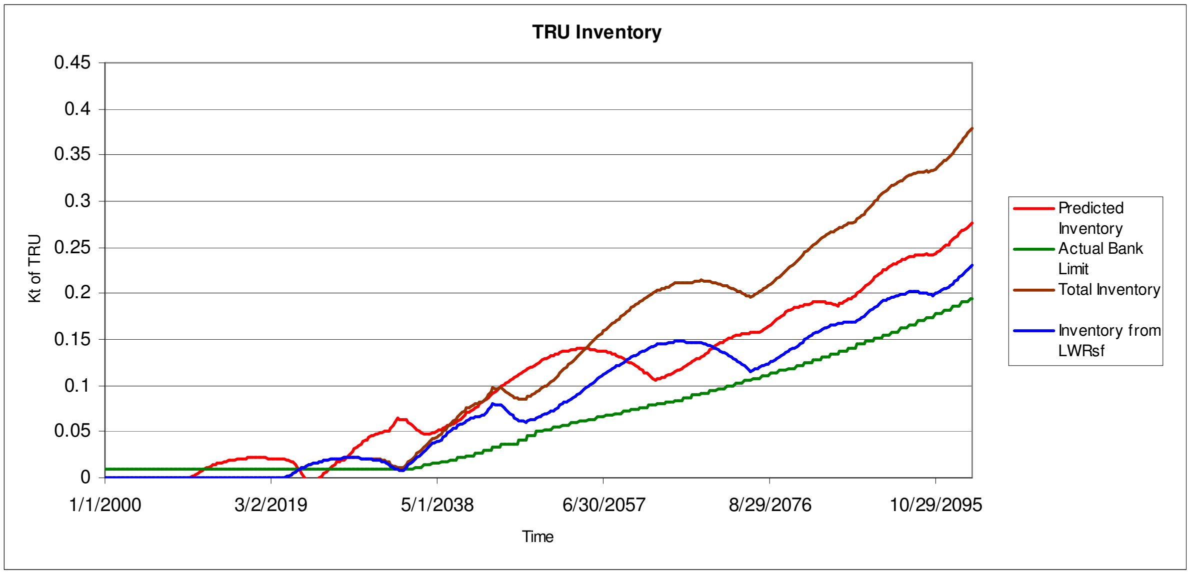

Figure 3-121: Case 6 TRU Inventory with 3 Year Lead Time

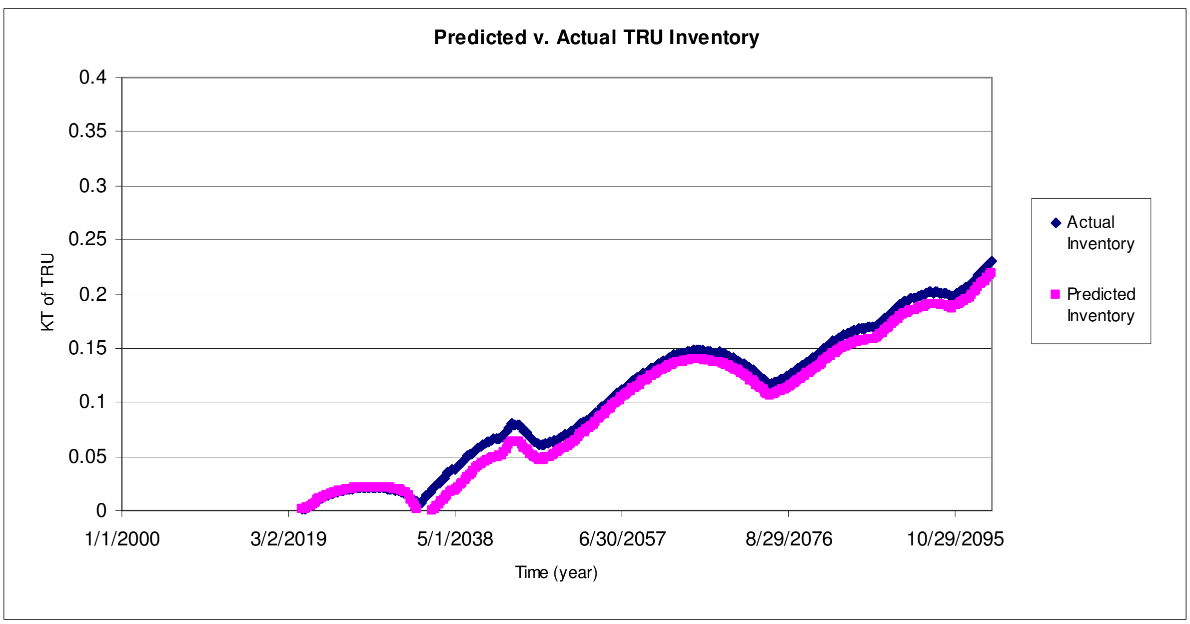

Figure 3-122: Case 6 Predicted v. Actual Inventory with 3 Year Lead Time

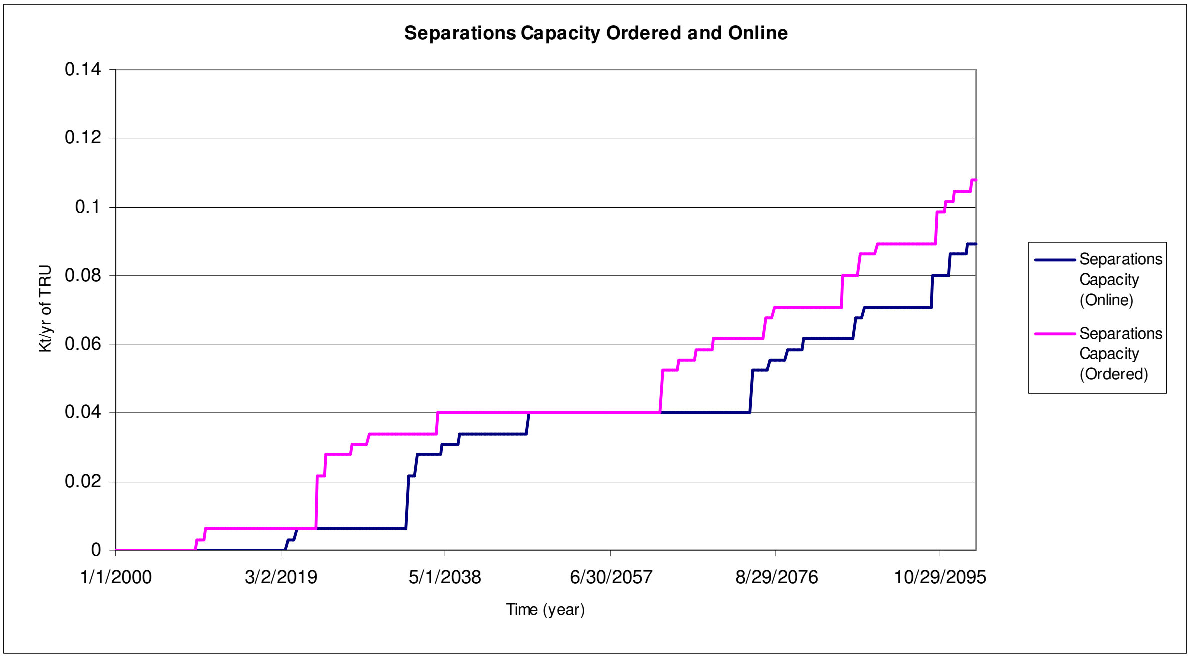

Figure 3-123: Case 6 Separations Capacity (kt/yr) with 3 Year Lead Time

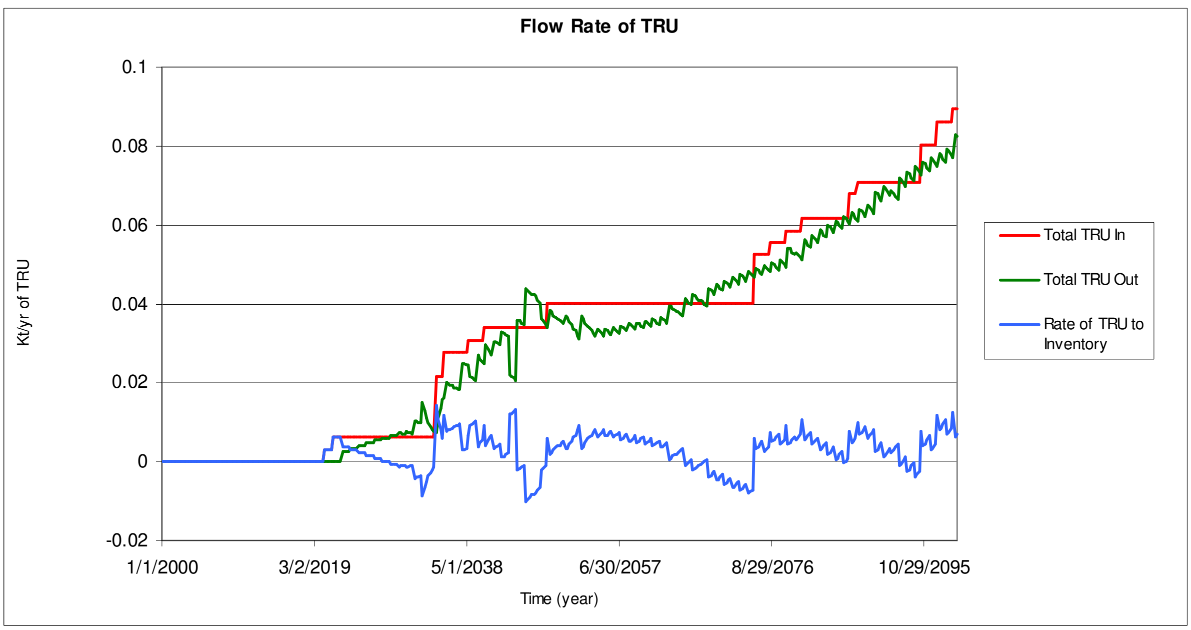

Figure 3-124: Case 6 Flow Rate of TRU to Predicted Inventory with 3 Year Lead Time

Lead Time of 1 Year

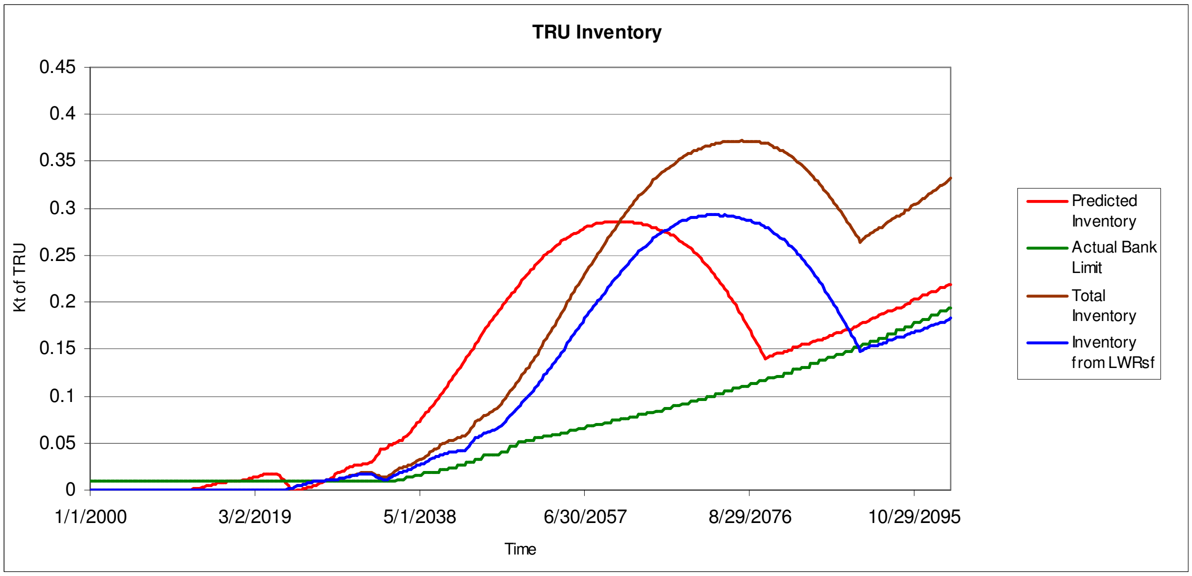

Figure 3-125: Case 6 TRU Inventory with 1 Year Lead Time

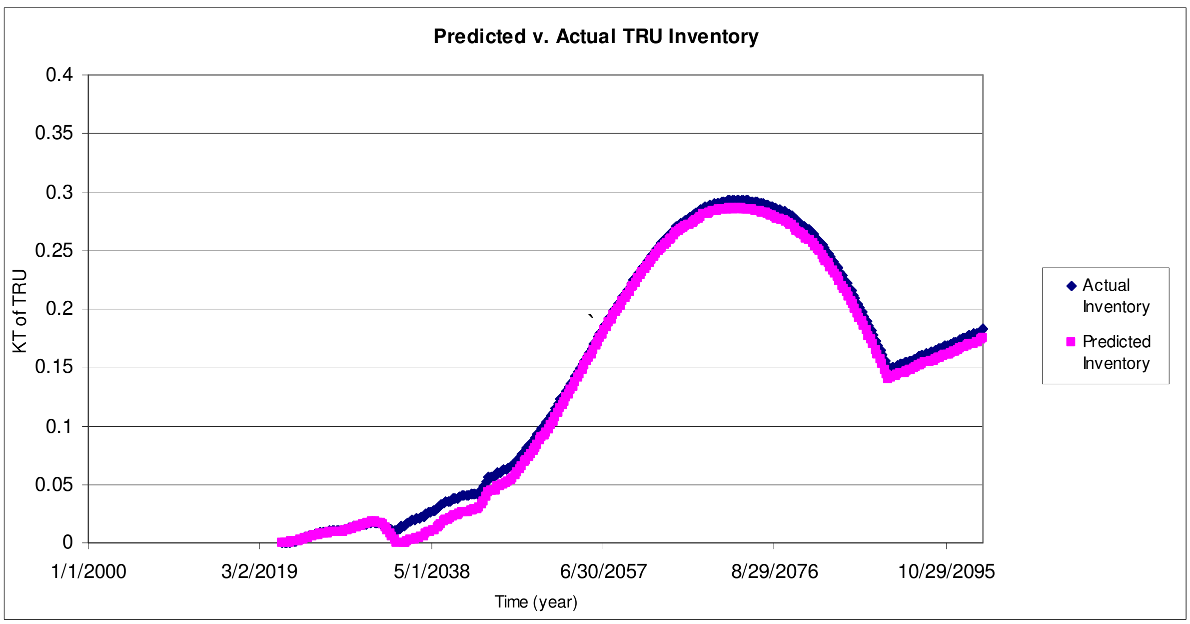

Figure 3-126: Case 6 Predicted v. Actual Inventory with 1 Year Lead Time

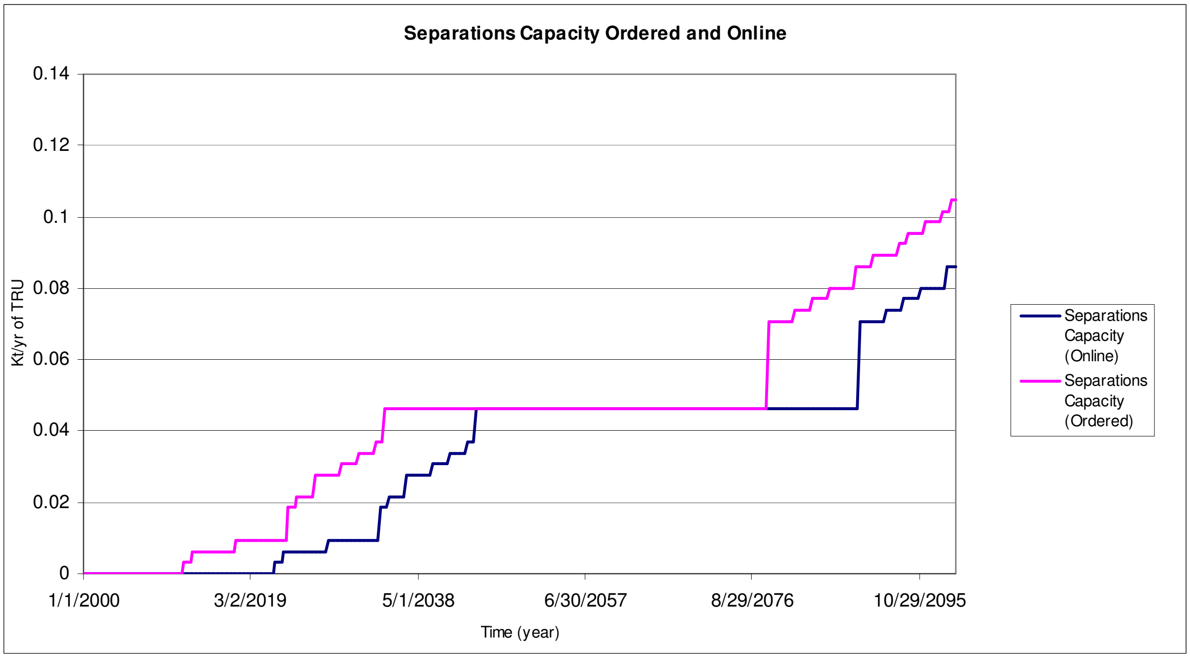

Figure 3-127: Case 6 Separations Capacity (kt/yr) with 1 Year Lead Time

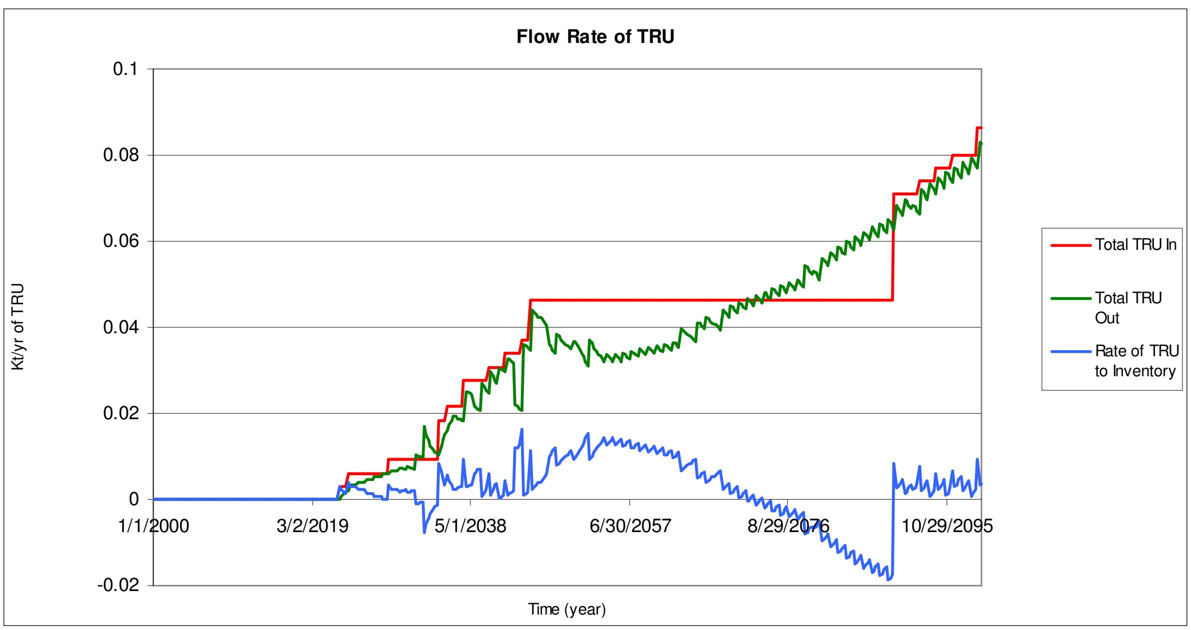

Figure 3-128: Case 6 Flow Rate of TRU with 1 Year Lead Time

The overall trend of the three Cases in Section 3.2.2 is that as the separations facility size decreases the lead time increases. In Case 4 with a 1 Kt/yr separation facility the lead time is 1 year. Case 5 proves a lead time of 4 years for a separation facility size of 0.5 Kt/yr is the most optimum. With a separations facility size of 0.25 Kt/yr, Case 6 proved that a lead time of 5 years is the best scenario.

3.2.3 New FBR Ramped up to 100% of Growth Rate or Max Value

In the following cases the energy growth that is met by FBRs is ramped up over 25 years to 100%. During the rest of the simulation the model will build as many FBRs as the look-ahead calculation will allow. Figure 3-129 and Figure 3-130 show the number of operating reactors and the deployed reactor capacity, respectively, for this build rate of FBRs. Cases 7 through 9 show the results of changing the separation facility size and lead time for the separation facilities.

The results presented in Figure 3-131 - Figure 3-134, Figure 3-135 - Figure 3-138, and Figure 3-139 - Figure 3-142 show the results for lead times of 7 years, 5 years, and 3 years, respectively.

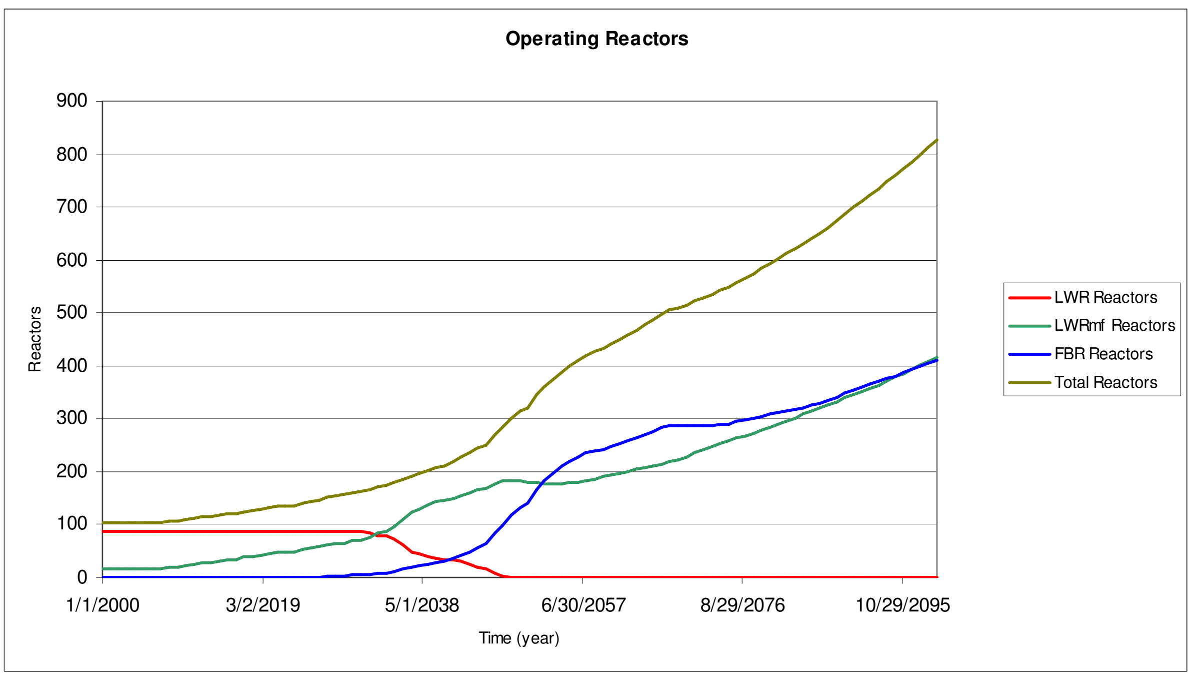

Figure 3-129: Case 7 Operating Reactors

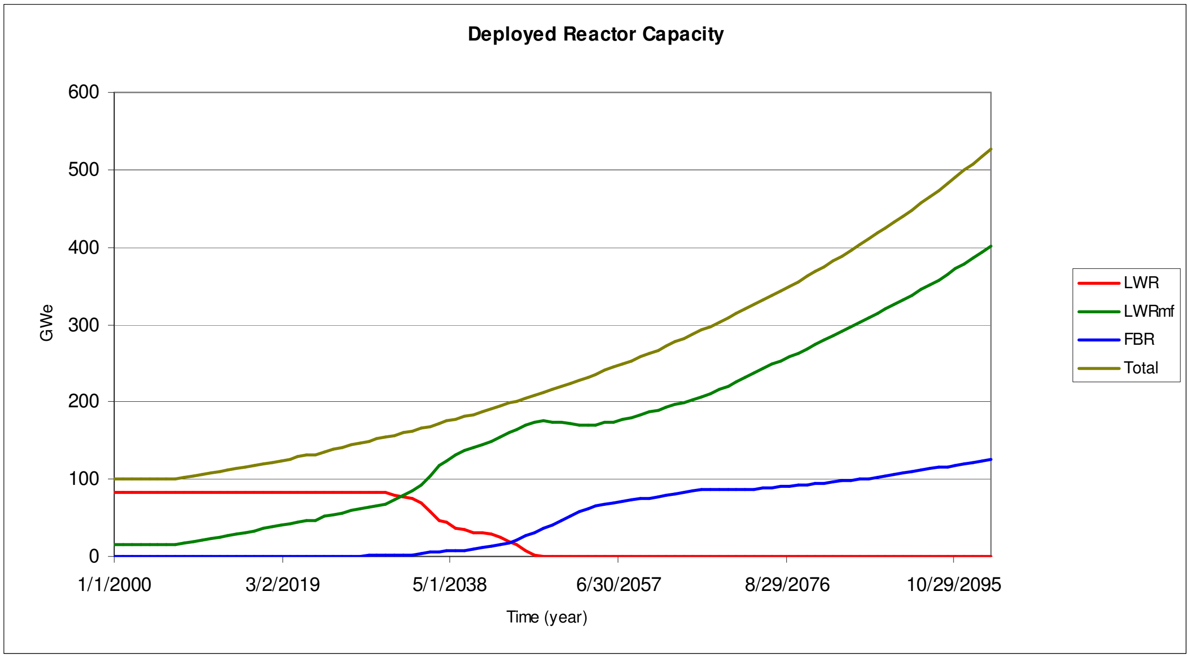

Figure 3-130: Case 7 Deployed Reactor Capacity

3.2.3.1 Case 7 Separation Facility Size of 1 Kt/yr

<u>Summary of Case 7</u>

In each scenario of Case 7 the simulation built too many separation facilities causing the simulation to have excess separations capacity around the year 2060. This can be seen in Figure 3-132, where the predicted inventory drastically increases as the actual inventory starts to decline. The actual inventory decreases because the amount of spent fuel available to separate has dropped below the total capacity of all separation facilities. There is still enough spent fuel to supply all of the operating FBRs; however, there is simply not enough spent fuel for all of the separation facilities. The predicted inventory cannot take into account this drop in spent fuel to separations because it assumes that separation facilities operate at 100% capacity all the time. This is why Figure 3-132 shows a large difference between the predicted and actual separated material inventory. The 5 and 3 year lead times do have a smaller number of separations capacity coming online (Figure 3-137 and Figure

3-139), however they still produce a very large inventory with excess separations capacity. The 4 and 1 year lead times produced the same results, so that data were not presented in this thesis.

Lead Time of 7 Years

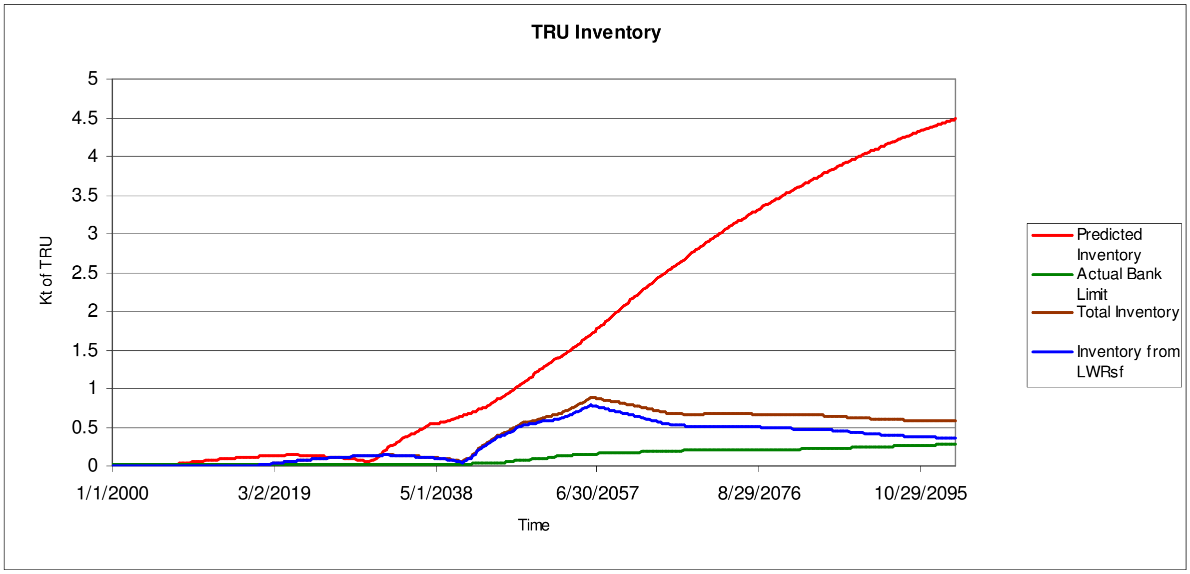

Figure 3-131: Case 7 TRU Inventory with 7 Year Lead Time

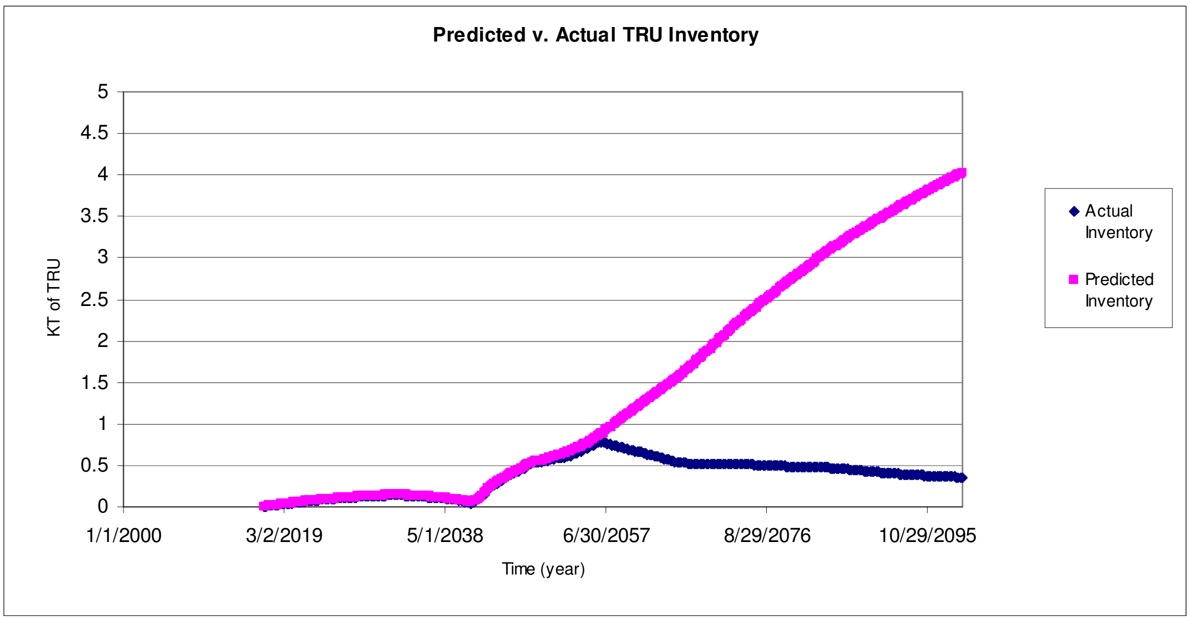

Figure 3-132: Case 7 Predicted v. Actual Inventory with 7 Year Lead Time

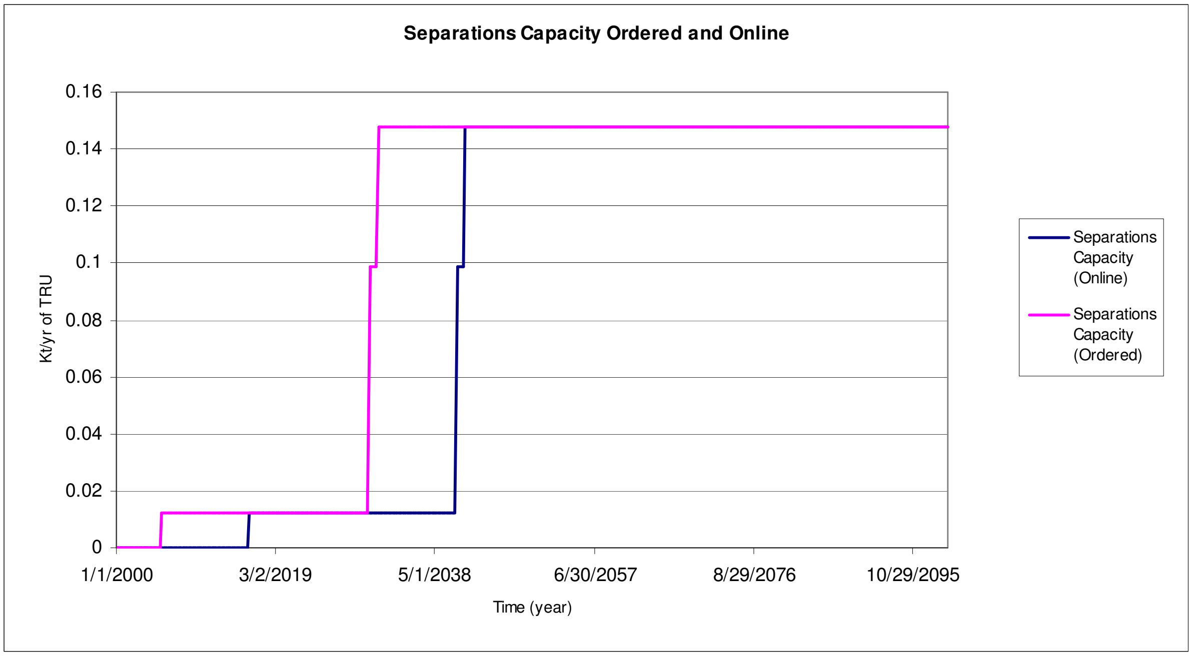

Figure 3-133: Case7 Separations Capacity (kt/yr) with 7 Year Lead Time

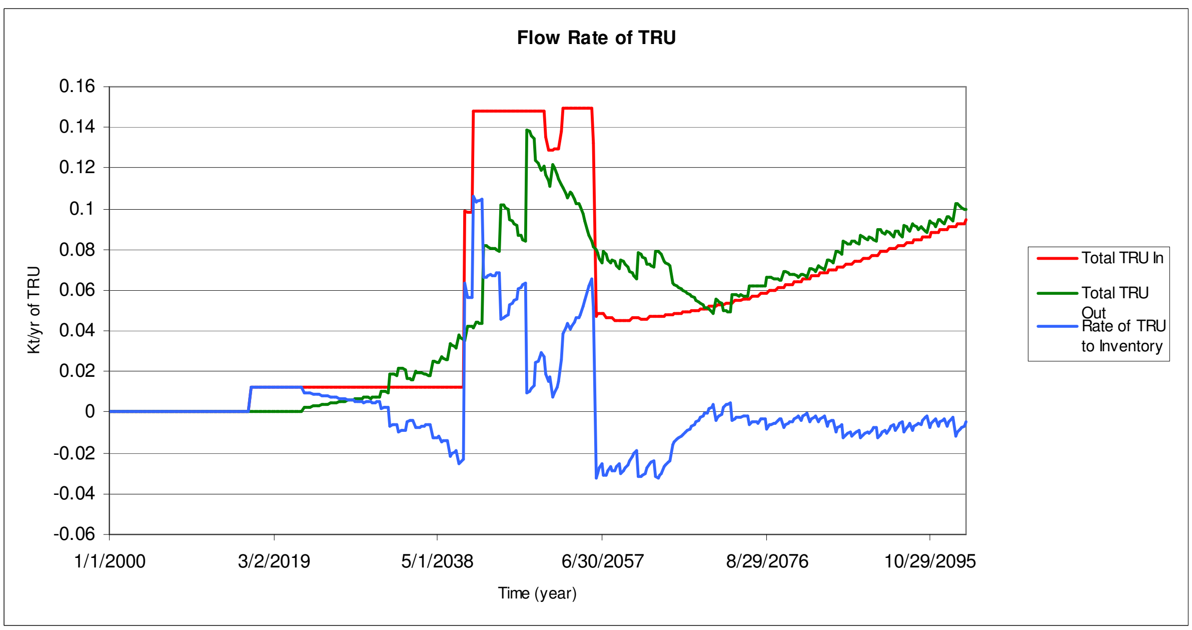

Figure 3-134: Case 7 Flow Rate of TRU to Predicted Inventory with 7 Year Lead Time

Lead Time of 5 Years

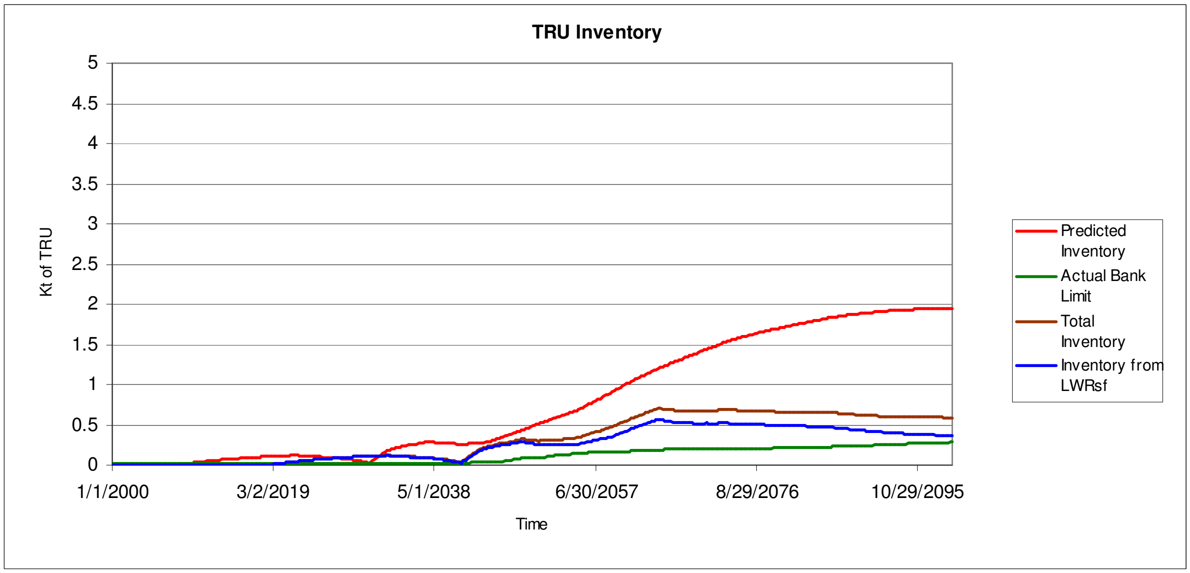

Figure 3-135: Case 7 TRU Inventory with 5 Year Lead Time

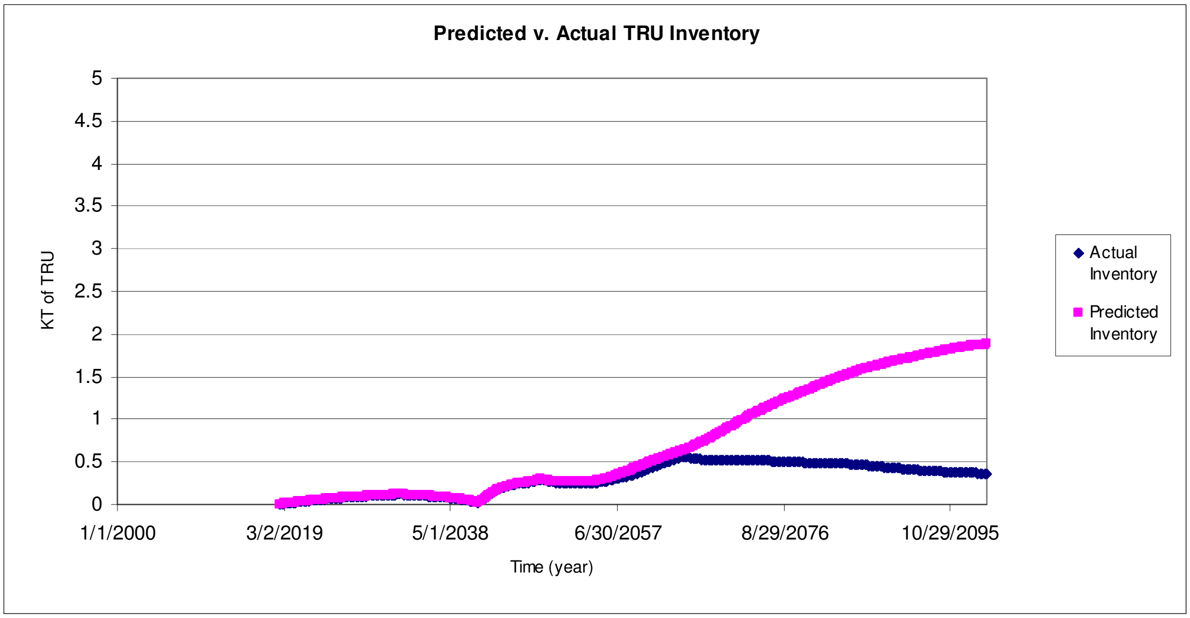

Figure 3-136: Case 7 Predicted v. Actual Inventory with 5 Year Lead Time

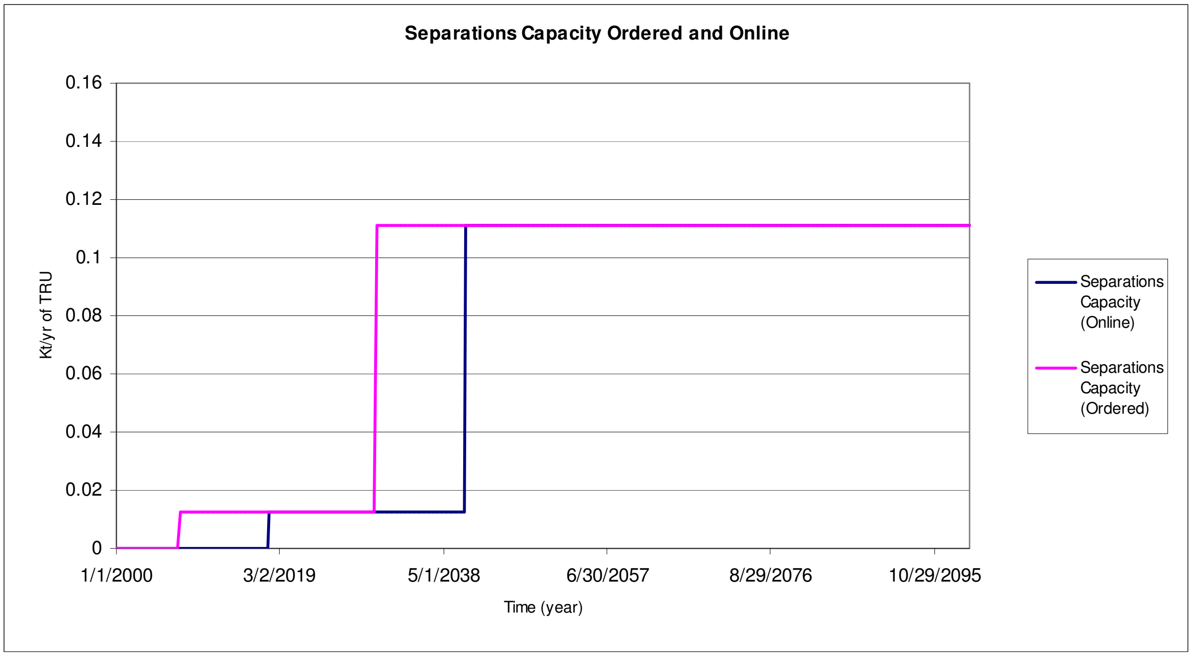

Figure 3-137: Case 7 Separations Capacity (kt/yr) with 5 Year Lead Time

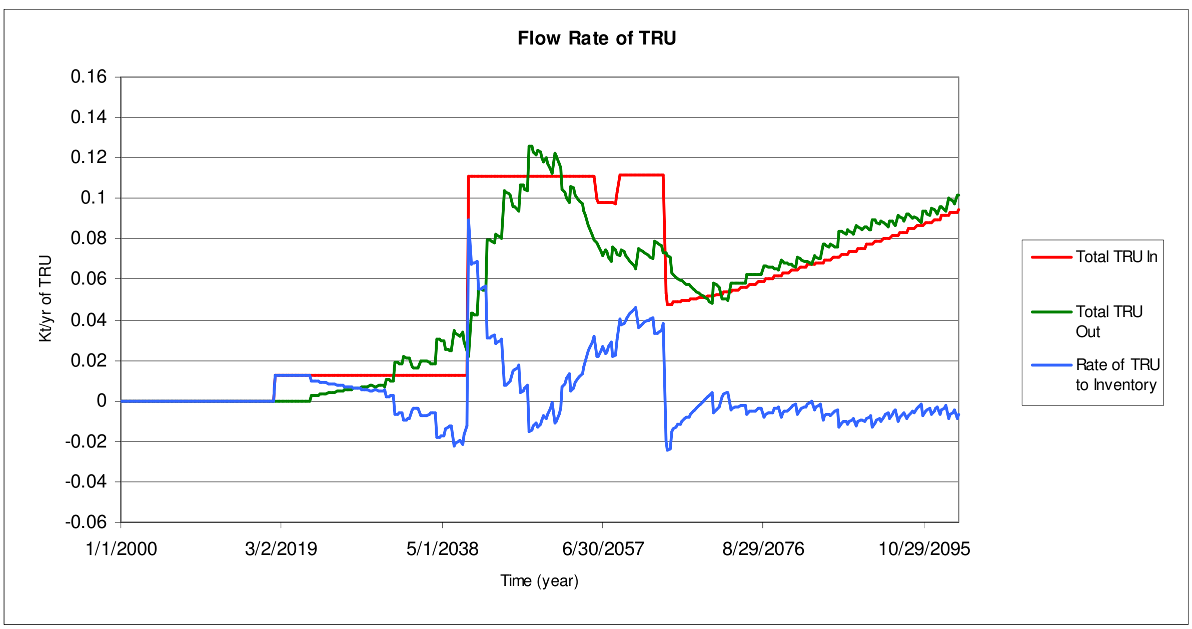

Figure 3-138: Case 7 Flow Rate of TRU to Predicted Inventory with 5 Year Lead Time

Lead Time of 3 Years

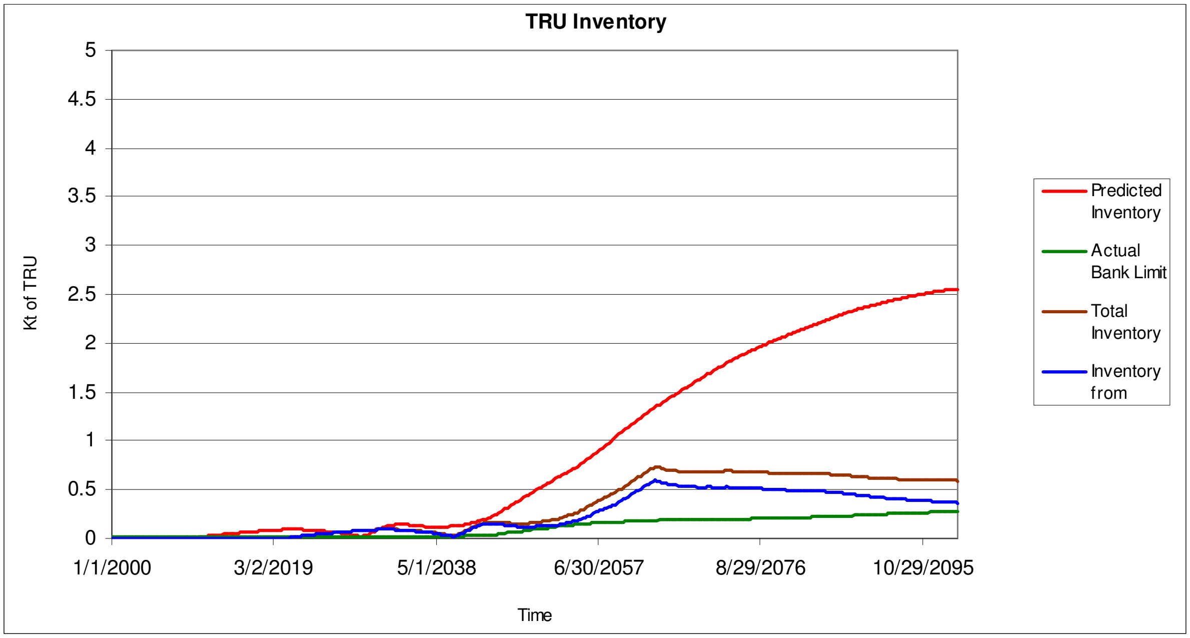

Figure 3-139: Case 7 TRU Inventory with 3 Year Lead Time

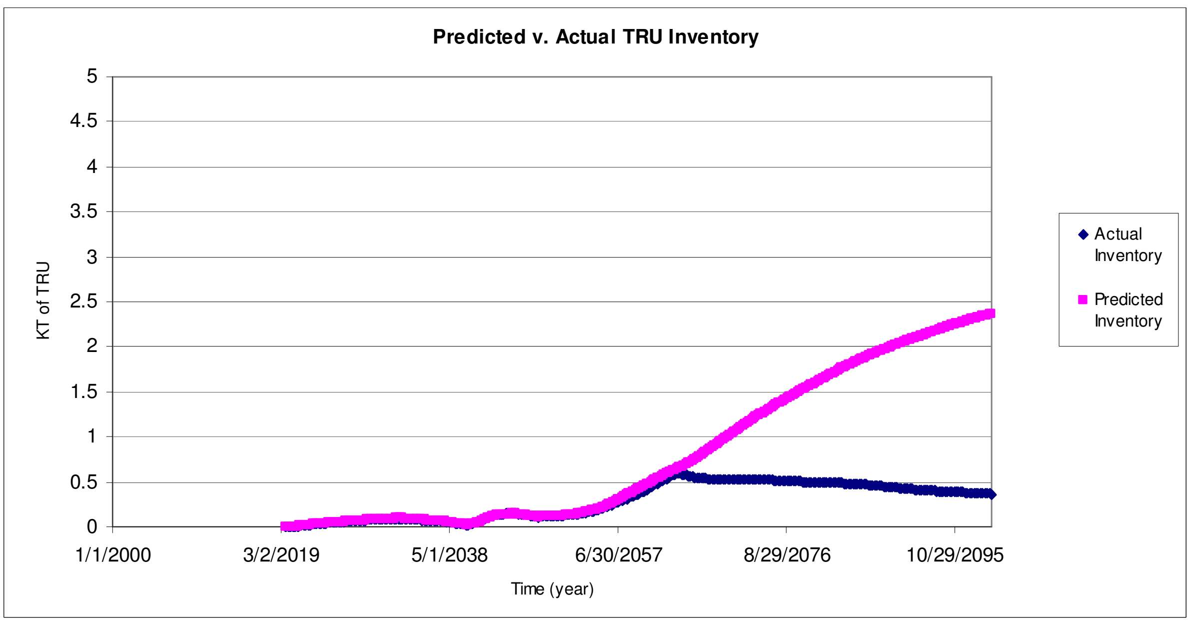

Figure 3-140: Case 7 Predicted v. Actual Inventory with 3 Year Lead Time

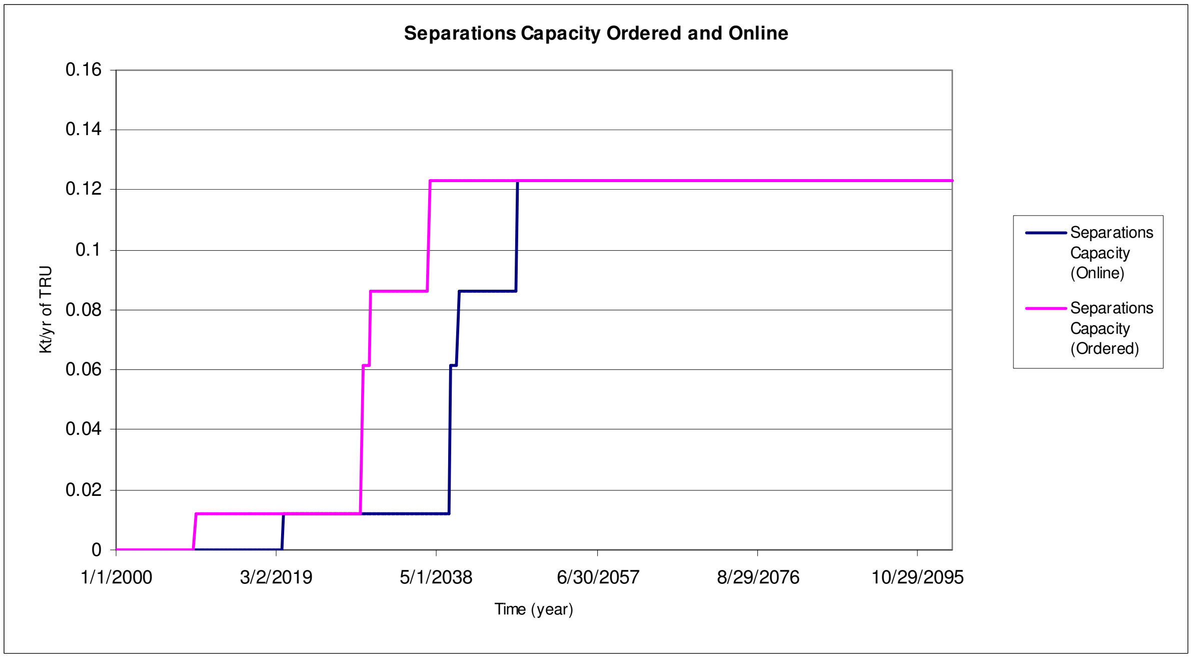

Figure 3-141: Case 7 Separations Capacity (kt/yr) with 3 Year Lead Time

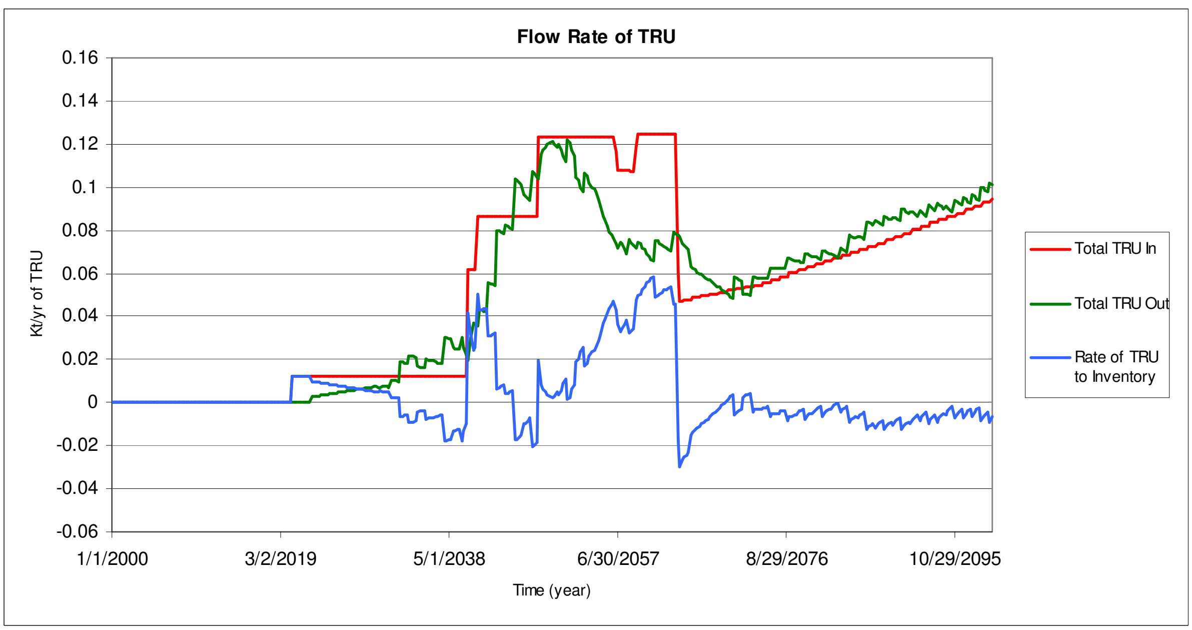

Figure 3-142: Case 7 Flow Rate of TRU to Predicted Inventory with 3 Year Lead Time

3.2.3.2 Case 8 Separation Facility Size of 0.5 Kt/yr

Summary of Case 8

The separation facility size of 0.5 Kt/yr with a lead time of 7 years produced the most accurate results because the predicted and actual inventories were very similar throughout the entire simulation. This scenario did not build nearly as much excess separations capacity as the 1 Kt/yr facility simulation. There is only a small amount of excess separations capability that starts around 2080 (Figure 3-144). Otherwise the predicted inventory before year 2080 matches up with the actual inventory (Figure 3-144) and the actual inventory oscillates slightly above the bank limit (Figure 3-143). The build rate is not the most spread out build rate; however, it brings on a smaller amount of capacity than Case 7. When the lead time was decreased, it caused the model to build too much separations capacity and therefore too much excess capacity.

The results presented in Figure 3-143 - Figure 3-146 and Figure 3-147 - Figure 3-150 show the data for the separation facility lead times of 7 years and 5 years, respectively.

Lead Time of 7 Years

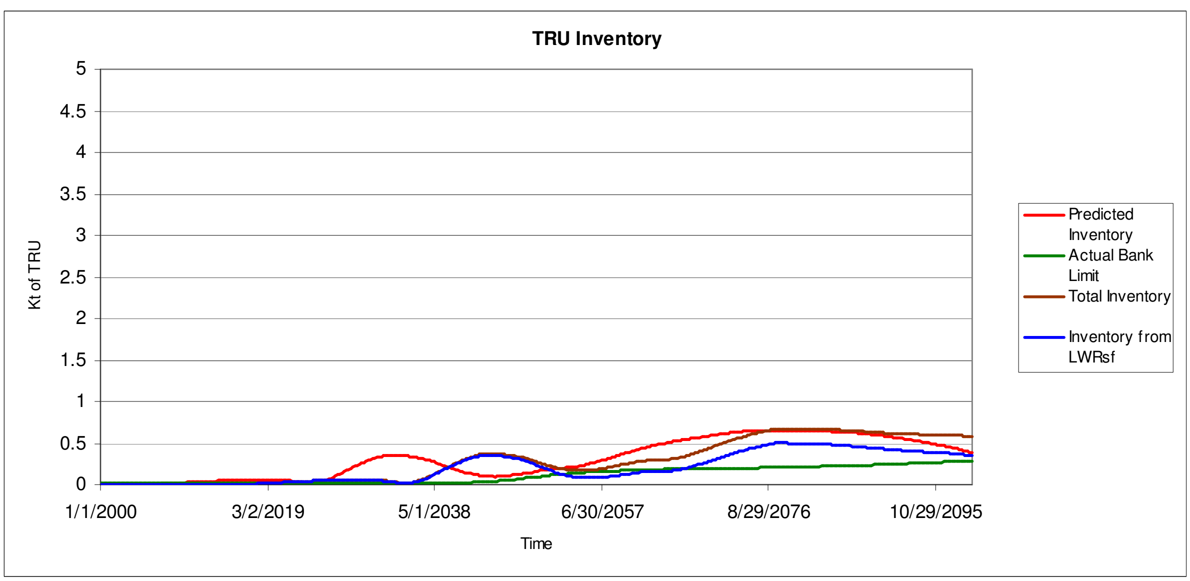

Figure 3-143: Case 8 TRU Inventory with 7 Year Lead Time

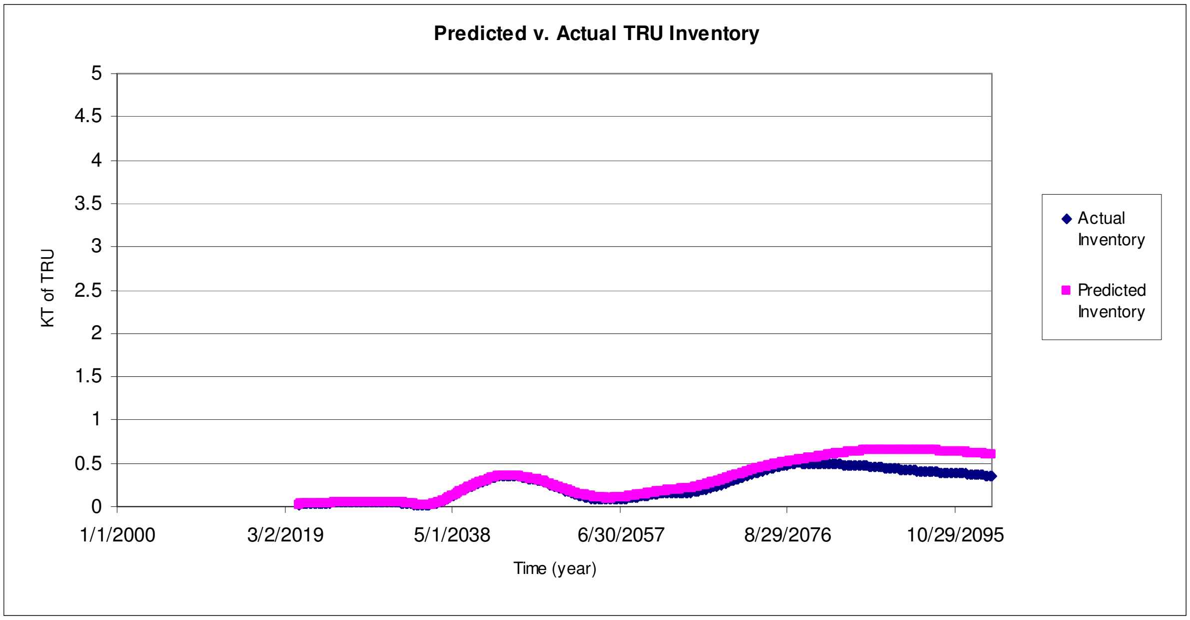

Figure 3-144: Case 8 Predicted v. Actual Inventory with 7 Year Lead Time

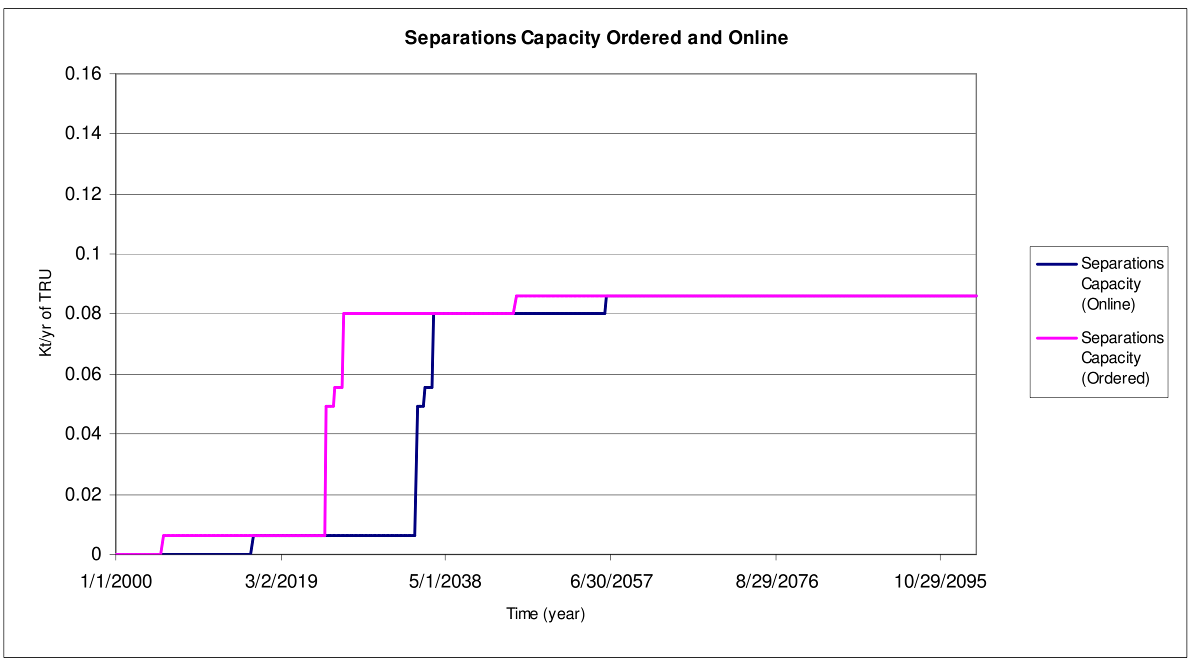

Figure 3-145: Case 8 Separations Capacity (kt/yr) with 7 Year Lead Time

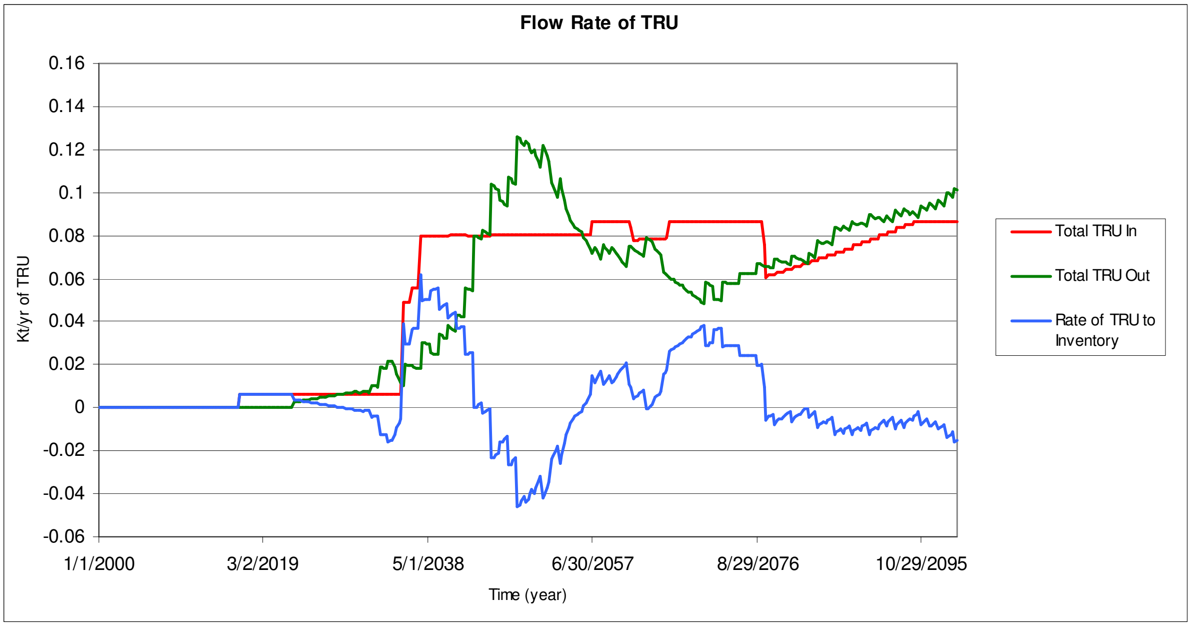

Figure 3-146: Case 8 Flow Rate of TRU to Predicted Inventory with 7 Year Lead Time

Lead Time of 5 Years

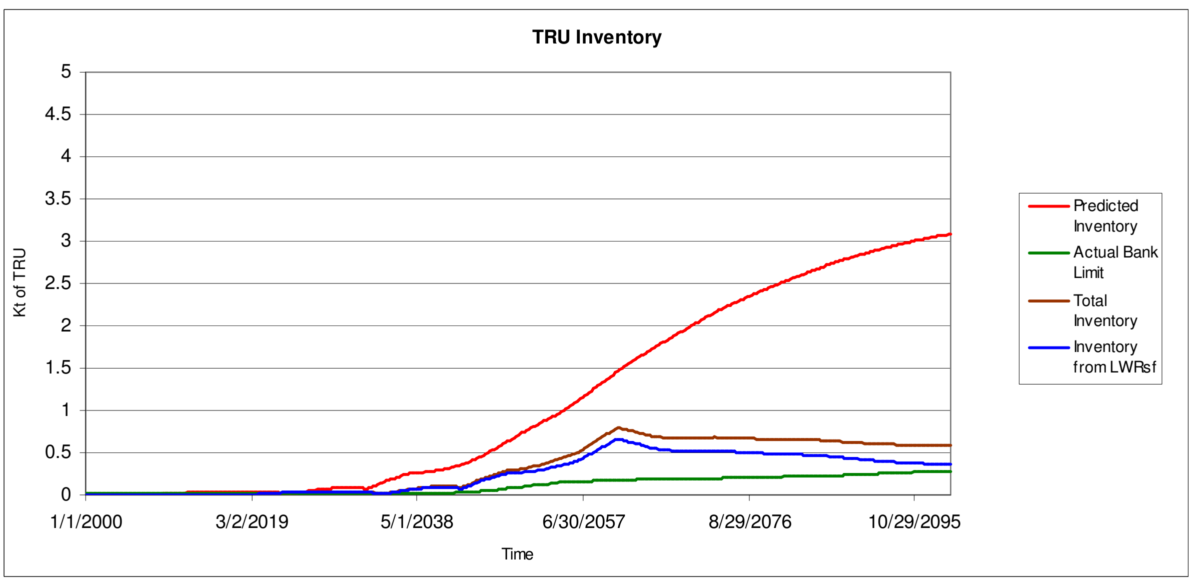

Figure 3-147: Case 8 TRU Inventory with 5 Year Lead Time

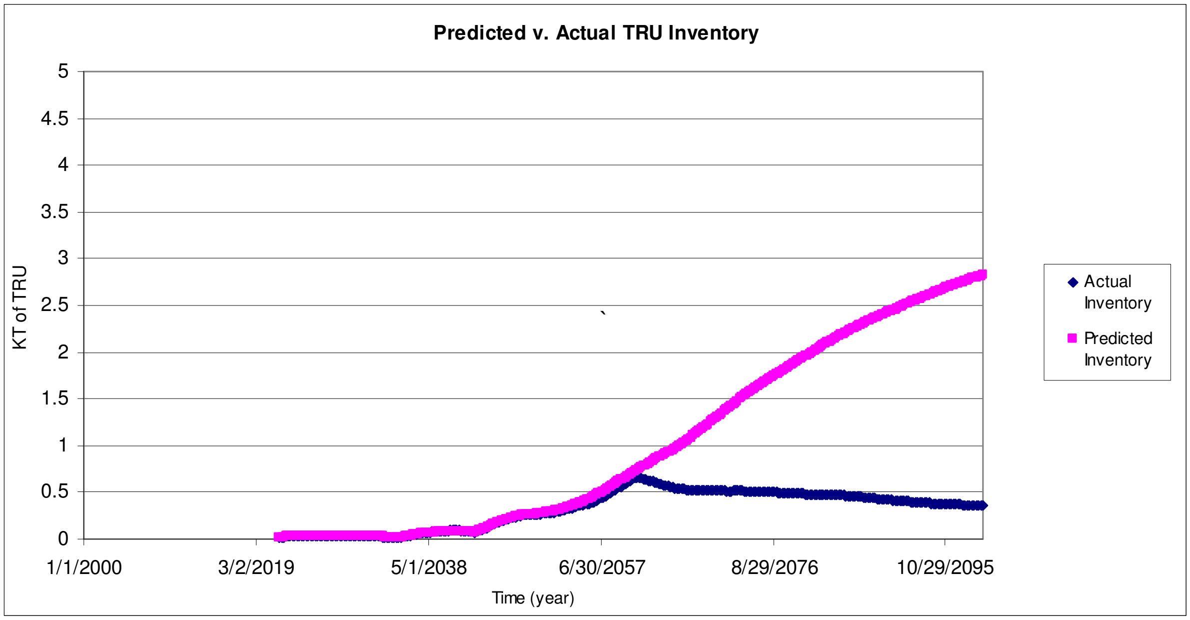

Figure 3-148: Case 8 Predicted v. Actual Inventory with 5 Year Lead Time

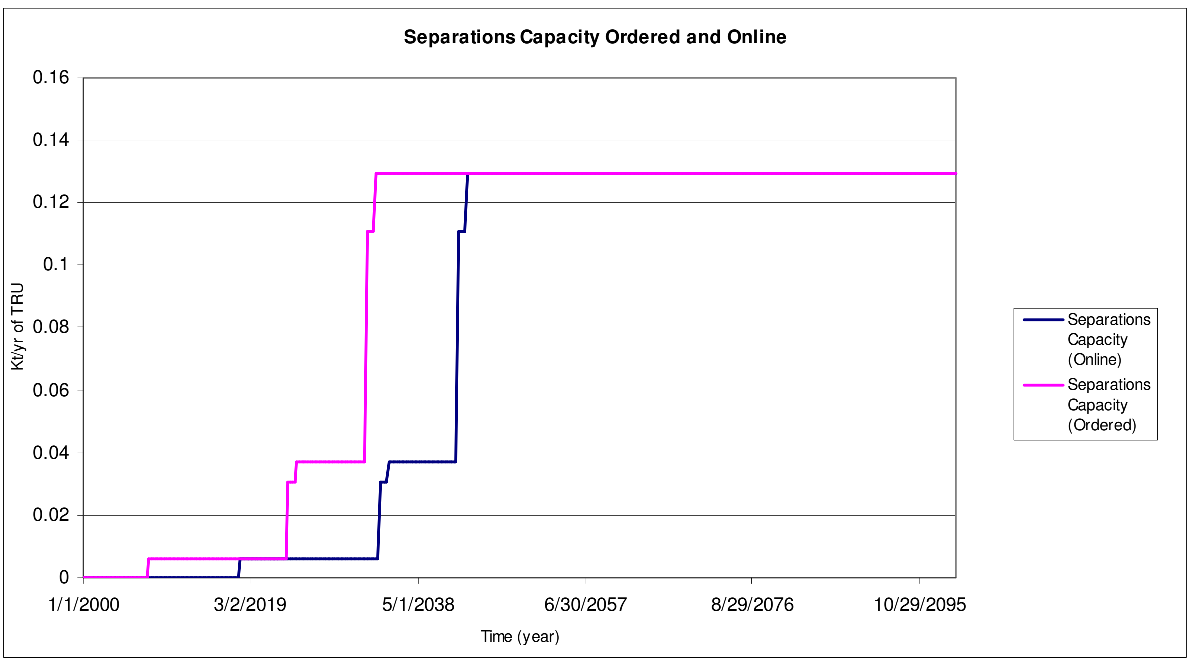

Figure 3-149: Case 8 Separations Capacity (kt/yr) with 5 Year Lead Time

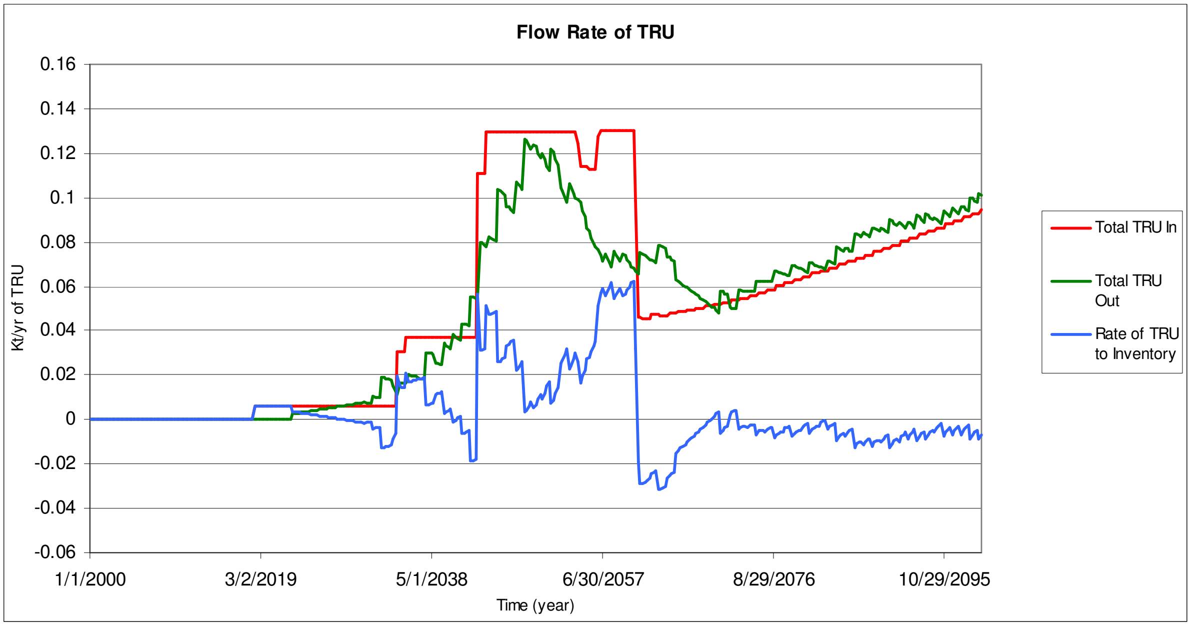

Figure 3-150: Case 8 Flow Rate of TRU to Predicted Inventory with 5 Year Lead Time

3.2.3.3 Case 9 Separation Facility Size of 0.25 Kt/yr

<u>Summary of Case 9</u>

Case 9 is very similar to Case 8 as they behave almost identical. There are a few differences though; the separations capacity is slightly lower than that for Case 8 (Figure 3-153). This allows the simulation to delay the onset of excess separations capacity by roughly 5 years (Figure 3-156). Similar to Case 8, when the lead time was decreased, too much separations capacity was built and lead to large excess separations capacity.

The results presented in Figure 3-151 - Figure 3-154 and Figure 3-155 - Figure 3-158 show the results for the lead times of 7 years and 5 years, respectively.

<u>Lead Time of 7 Years</u>

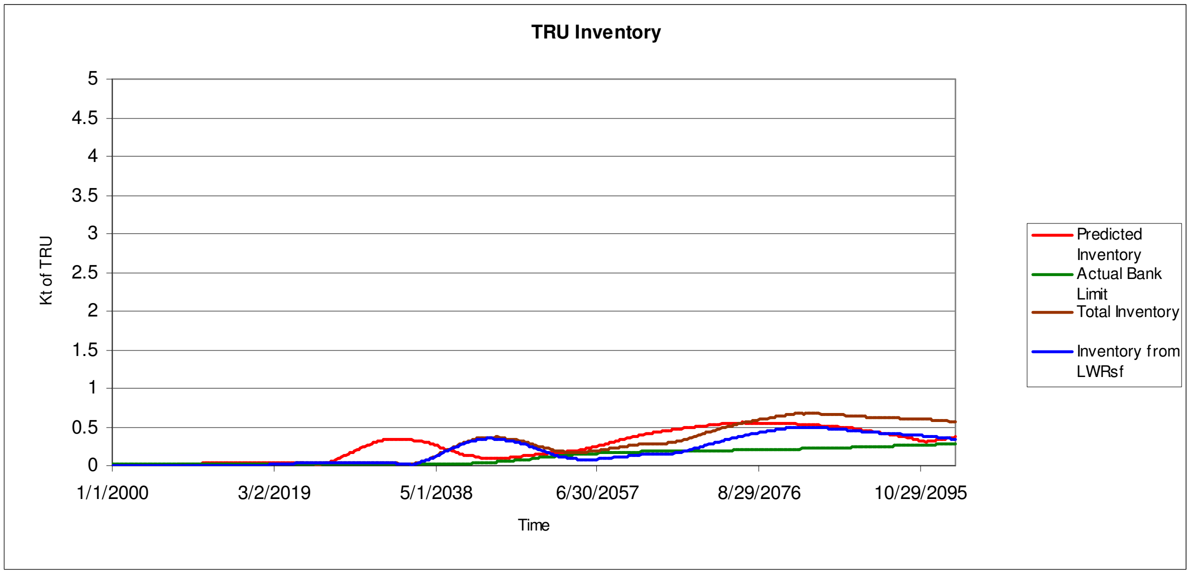

Figure 3-151: Case 9 TRU Inventory with 7 Year Lead Time

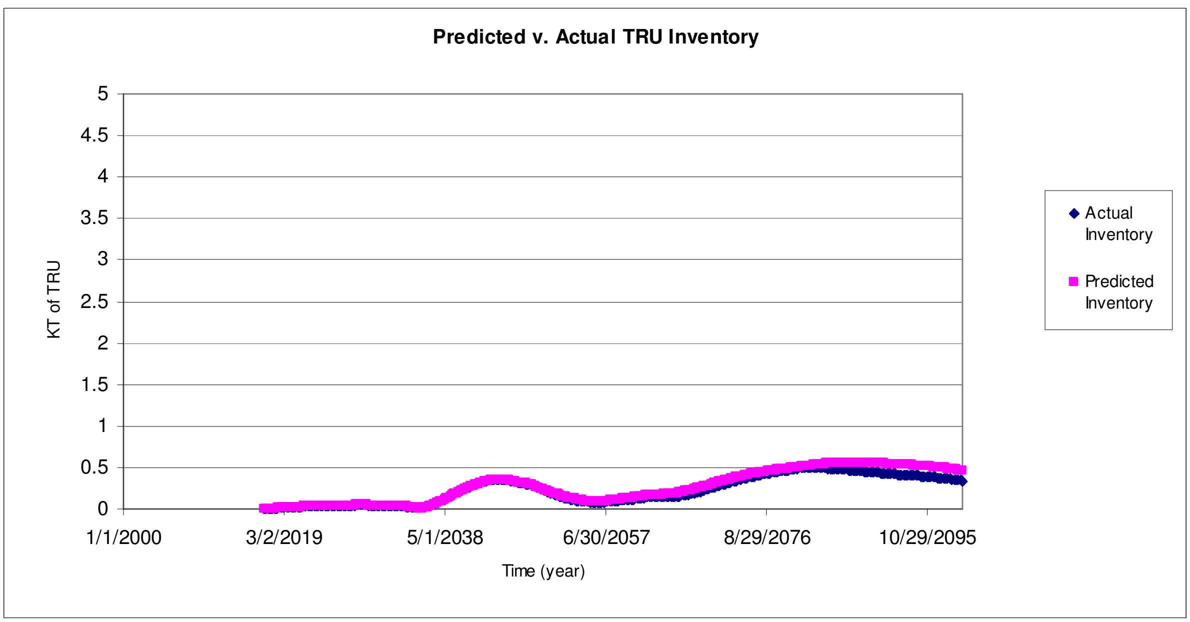

Figure 3-152: Case 9 Predicted v. Actual Inventory with 7 Year Lead Time

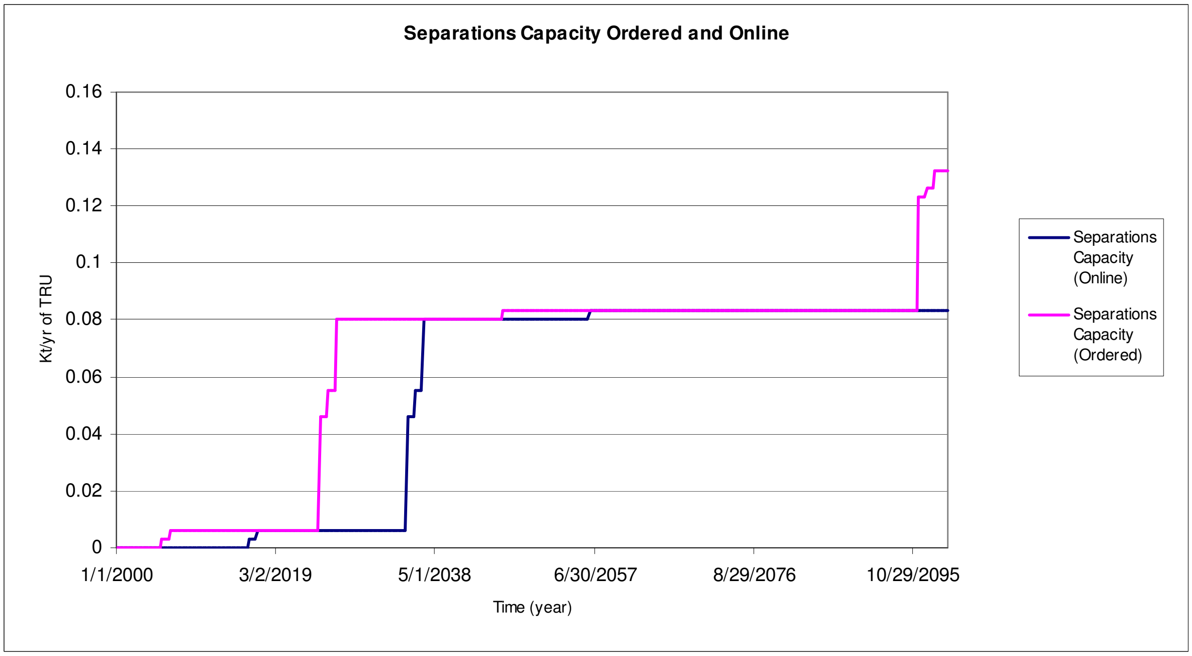

Figure 3-153: Case 9 Separations Capacity (kt/yr) with 7 Year Lead Time

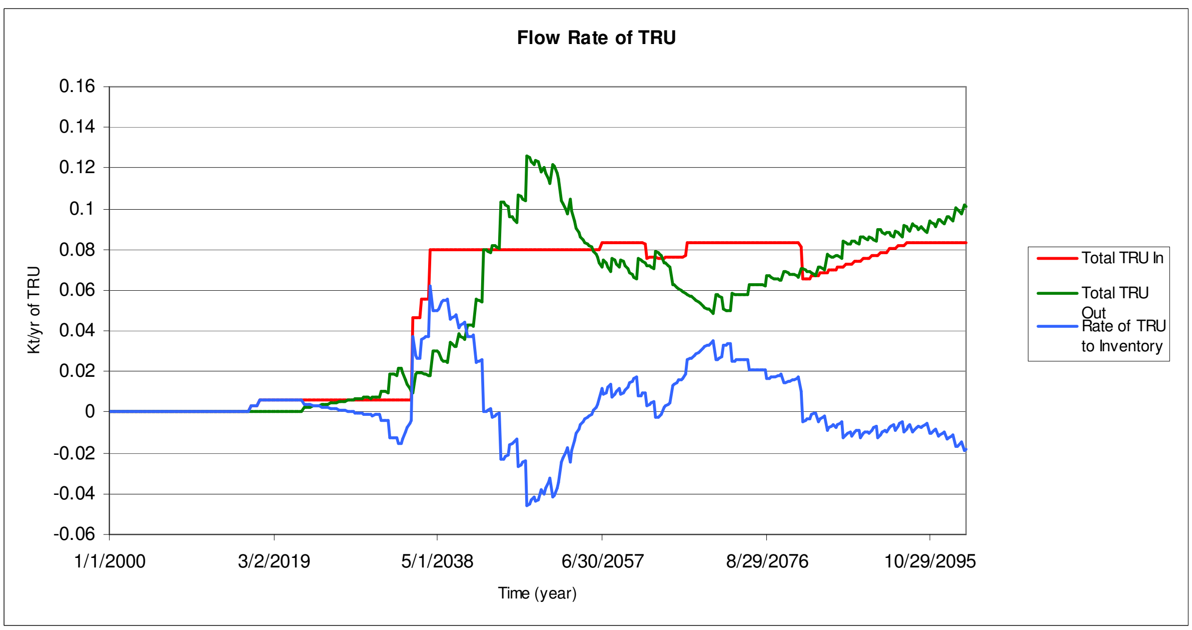

Figure 3-154: Case 9 Flow Rate of TRU to Predicted Inventory with 7 Year Lead Time

Lead Time of 5 Years

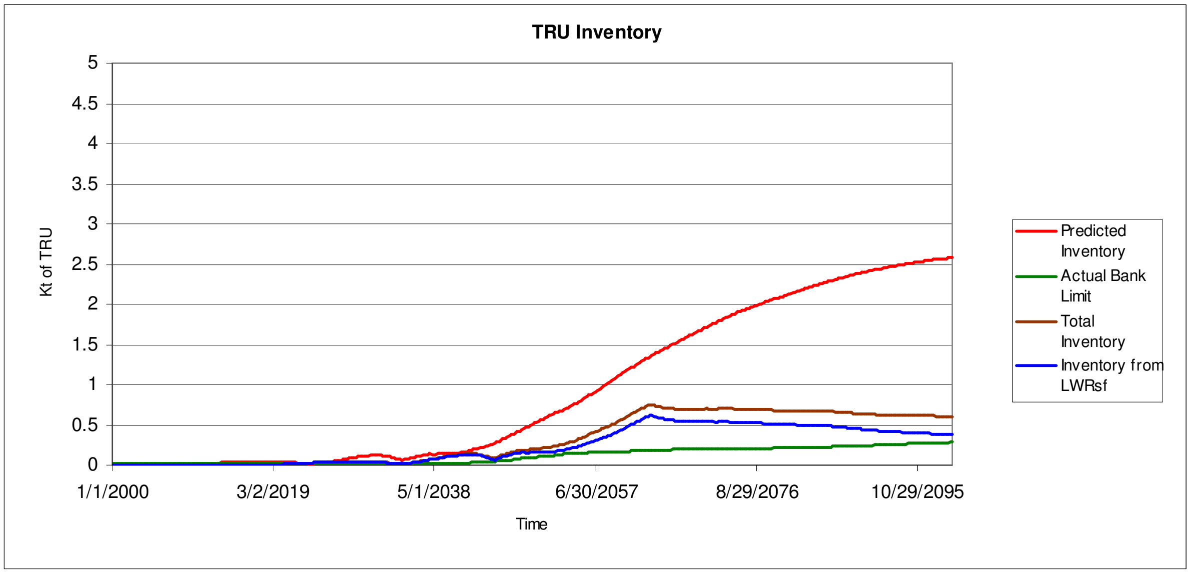

Figure 3-155: Case 9 TRU Inventory with 5 Year Lead Time

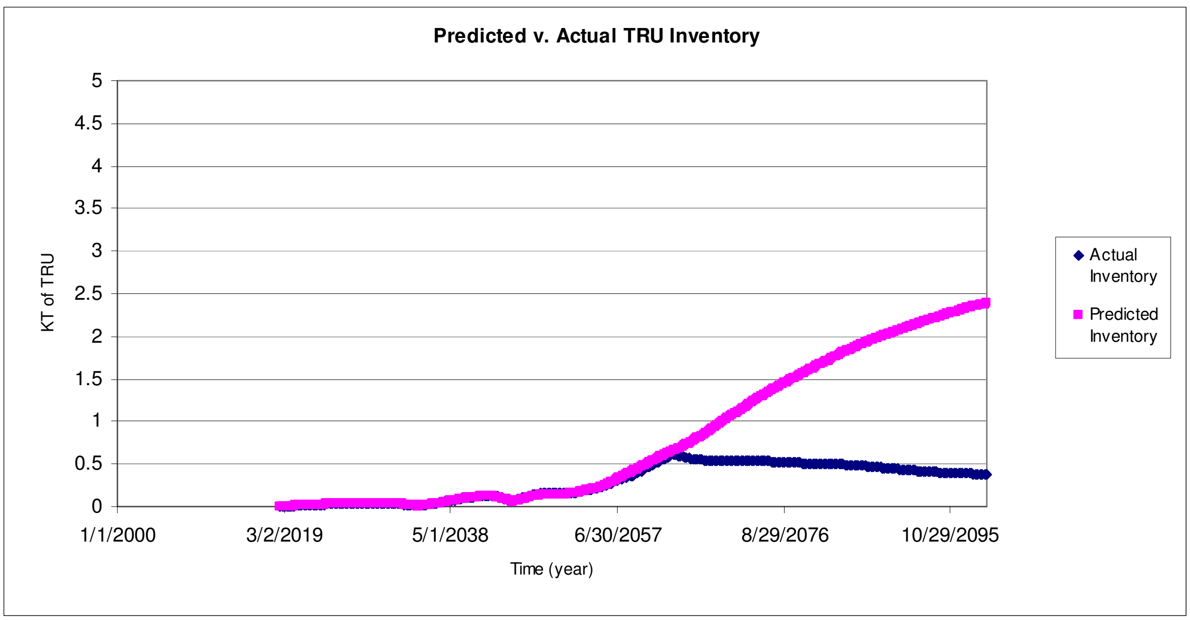

Figure 3-156: Case 9 Predicted v. Actual Inventory with 5 Year Lead Time

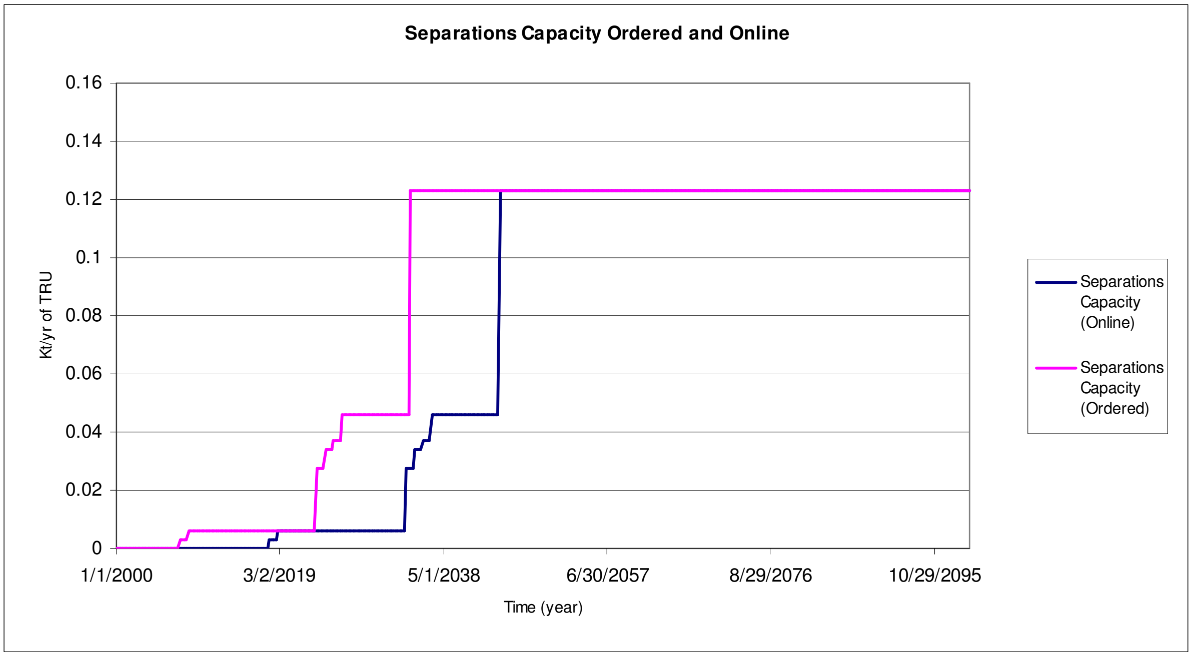

Figure 3-157: Case 9 Separations Capacity (kt/yr) with 5 Year Lead Time

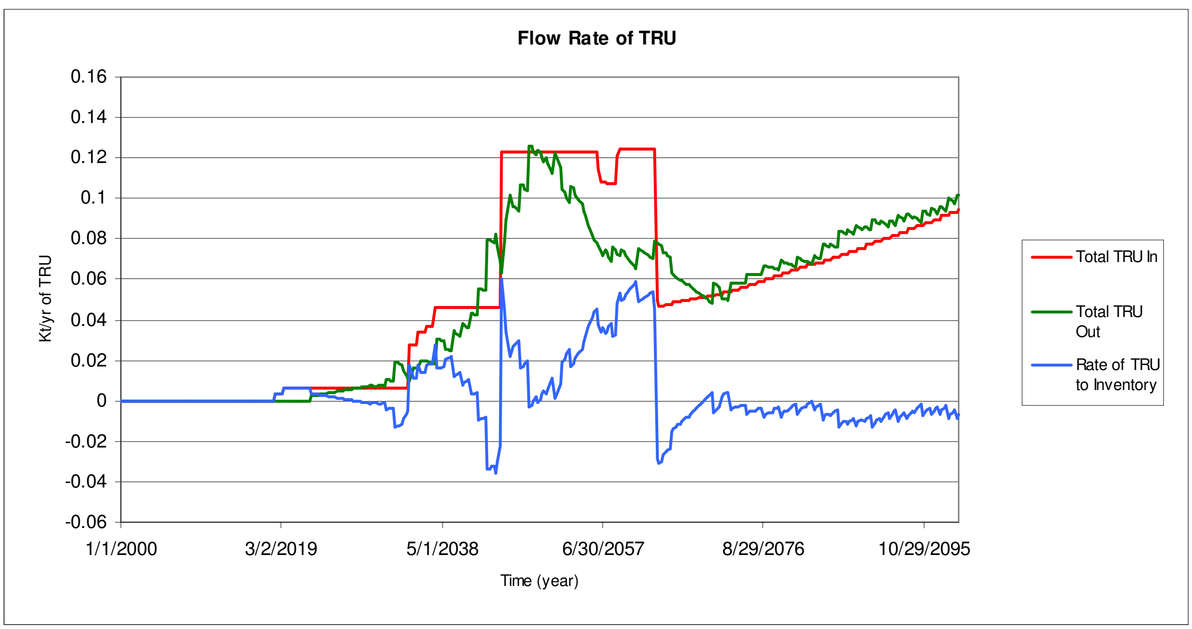

Figure 3-158: Case 9 Flow Rate of TRU to Predicted Inventory with 5 Year Lead Time

In summary with the much large build rate of separations facilities, the system was very vulnerable to building too much separations capacity. None of the 1 Kt/yr facility cases produced any positive results; however the 0.5 Kt/yr and 0.25 Kt/yr separation facilities produced fairly good results. There could be an increased accuracy if the lead time was increased; however, that is not feasible for this analysis. Table 3-1 shows a summary of the results from the Section 3.2.

Table 3-1: Summary of Results from Facility Ordering Analysis

Facility Size	Lead Time		
	10 % FBR Growth	20% FBR Growth	FBR Ramp up to 100%
1 kt/yr	Not Feasible	1 yr	Not Feasible
0.5 kt/yr	1yr	4 yr	7 yr
0.25 kt/yr	3yr	5 yr	7 yr

3.3 Results from Upset Scenarios

In this research two main upset scenarios will be analyzed: delay of LWRsf separation facilities coming online and a temporary shutdown of operating LWRsf separations facilities. The reference data for these upset scenarios is the Thorp separations facility built in England (5). The scenarios that will be analyzed are the most realistic scenarios from Section 3.2 that are found in Table 3-1. There will also be a small subset of scenarios that will be analyzed in addition to those found in Table 3-1. It is important to note that the predicted inventory does not have any feedback from the actual simulation; therefore, if there is a delay or a change in the separations capacity in the model the predicted inventory will not take this into account.

3.3.1 Delay of Facilities Coming Online

The first separation facilities under construction in each case were delayed by 9 years. The delay of 9 years was chosen in order to match the Thorp plant in England, where it experienced a total 20 year license and construction time (5). In the model aqueous separations facilities have a 1 year license time and a 10 year construction time, so 9 year was added as a delay. Table 3-2 shows all of the scenarios that will be analyzed with a 9 year construction delay on the first separation facilities ordered.

Table 3-2: Scenarios Analyzed with a 9 Year Delay on First Separations Plant

	10 % FBR Growth		20% FBR Growth		FBR Ramp up to 100%	
Scenario #	Facility Size	Lead Time	Facility Size	Lead Time	Facility Size	Lead Time
1	0.5 kt/yr	1 yr	1 kt/yr	1 yr	0.5 kt/yr	7 yr
2	0.25 kt/yr	3 yr	0.5 kt/yr	4 yr	0.25 kt/yr	7 yr
3	0.5 kt/yr	3 yr	0.25 kt/yr	5 yr	0.25 kt/yr	5 yr
4			0.25 kt/yr	7 yr		

3.3.1.1 New FBR Build Held at 10% of Energy Growth

During an upset event where a separations facility is delayed during construction, many FBRs that were ordered are delayed in starting as well. The overall trend in the results shows that for a longer lead time the number of reactors that are delayed decreases. The inventory of separated material and the predicted inventory of separated material will not match up because the prediction cannot foresee upset events in the model. The data presented in Table 3-3 shows the lost FBR GWe years. This value is the number of FBRs waiting to come online summed over time and multiplied by their GWe rating of 0.36GWe, which represents the lost GWe-yr of energy that is not supplied to the grid by FBRs.

In the following scenarios the results shown in Figure 3-159 - Figure 3-162, Figure 3-163 - Figure 3-166, and Figure 3-167 - Figure 3-170 are the results for Scenario 1, Scenario 2 and Scenario 3 of Table 3-3, respectively.

Table 3-3: Lost GWe Year for Separation Facility Delay with 10% FBR Growth

	10% FBR Growth		Lost FBR GWe Years
Scenario Number	Facility Size	Lead Time	
1	0.5 kt/yr	1 yr	35.28GWe-yr
2	0.25 kt/yr	3 yr	25.56GWe-yr
3	0.5 kt/yr	3 yr	23.04GWe-yr

Scenario 1: Separation Facility Size of 0.5 Kt/yr with 1 Year Lead Time and 10% FBR Growth

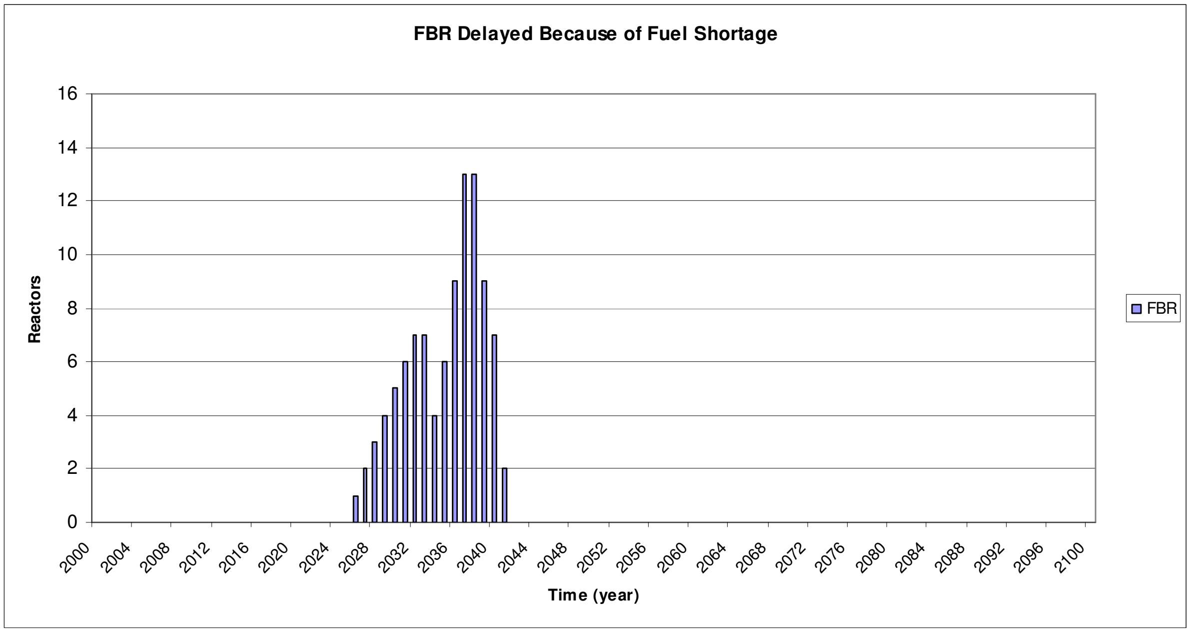

Figure 3-159: FBR Delayed at Startup

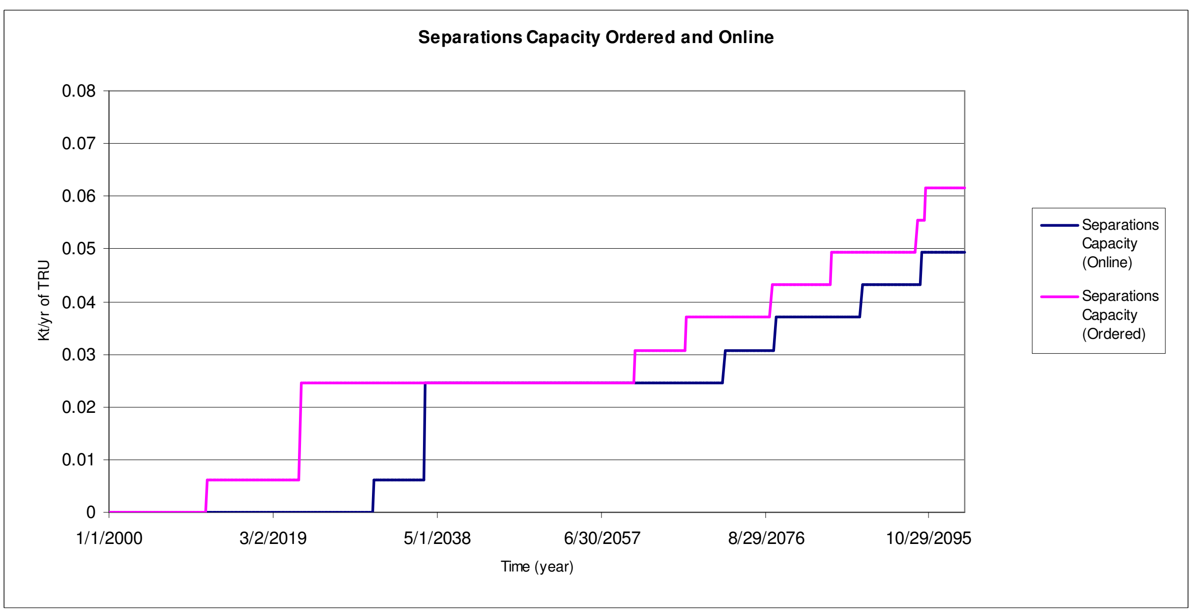

Figure 3-160: Separations Capacity with 9 Year Delay

The separations capacity in Figure 3-160 shows when separations facilities are ordered versus when they come online. The delay in this facility starting up can be particularly noticed when comparing this graph to the separation capacity in Figure 3-45.

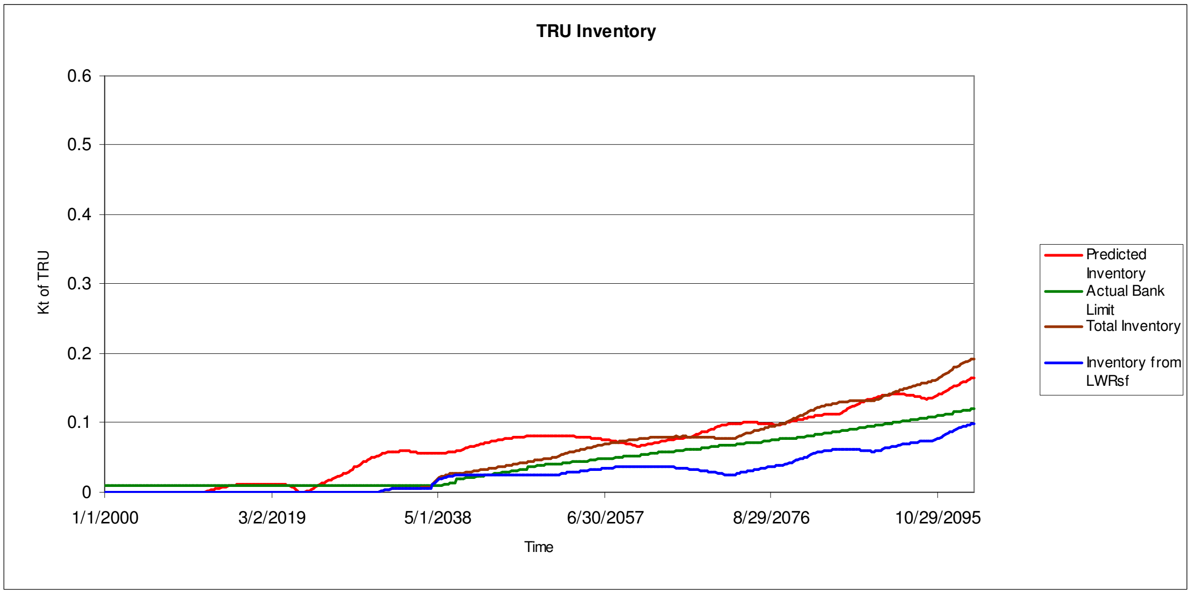

Figure 3-161: Inventory with 9 Year Delay

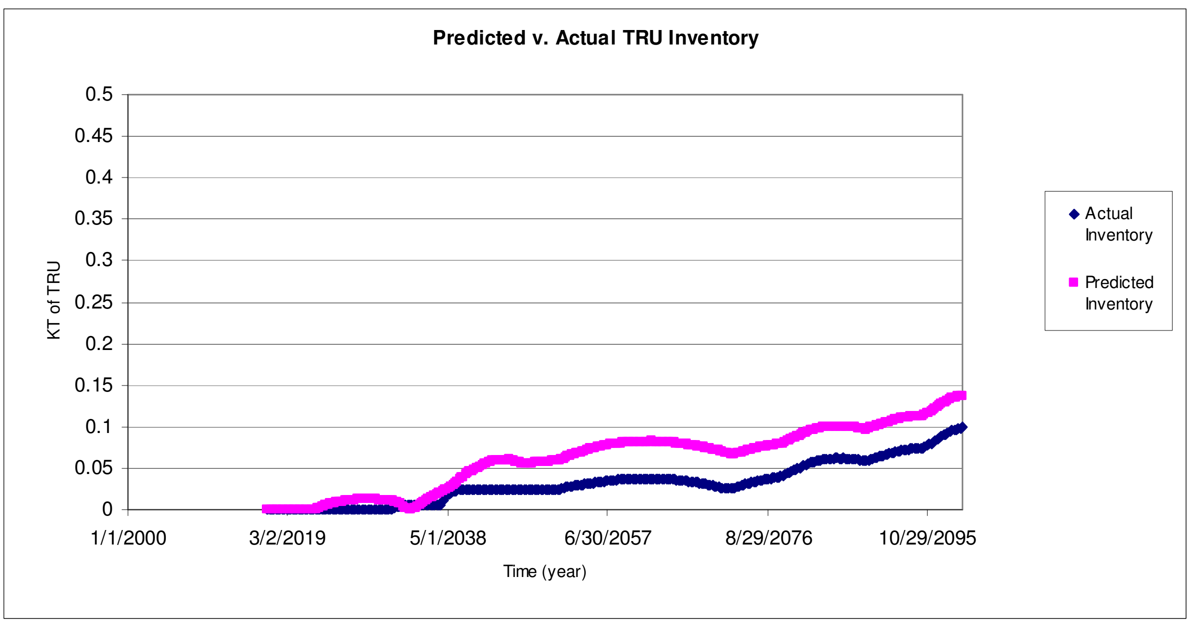

Figure 3-162: Predicted v. Actual Inventory with 9 Year Delay

The predicted and actual inventories are shifted in magnitude because the predicted inventory does not take into account the delay in construction time for the separation facility.

Figure 3-162 shows this shift in inventory level. One major consequence to this lack of feedback is that the actual inventory operates below the minimum bank limit for the duration of the simulation, which is shown in Figure 3-161.

<u>Scenario 2: Separation Facility Size of 0.25 kt/yr with a 3 year Lead Time and 10% FBR Growth</u>

Changing the separation facility size and increasing the lead time for the separation facility has a positive affect on the upset scenario. The number of reactors waiting for fuel in order to startup decreases and reactors are able to startup sooner (Figure 3-163). The increase in lead time also allows the actual inventory to operate closer to the bank limit than the previous scenario with a 1 year lead time and a larger separation facility size (Figure 3-165 and Figure 3-166).

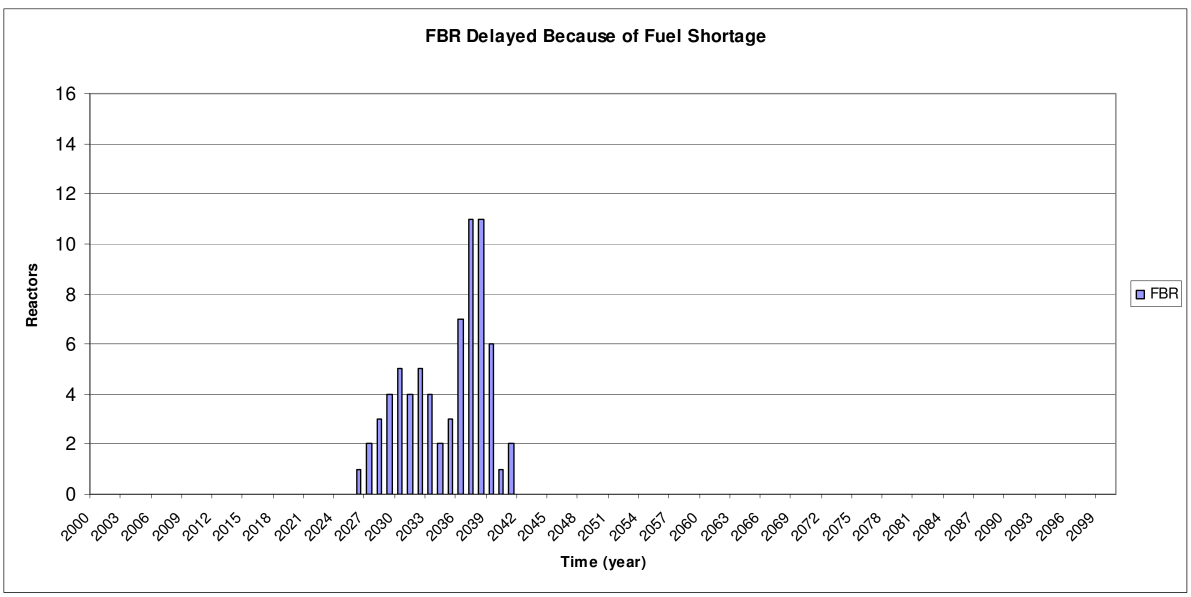

Figure 3-163: FBRs Delayed at Startup

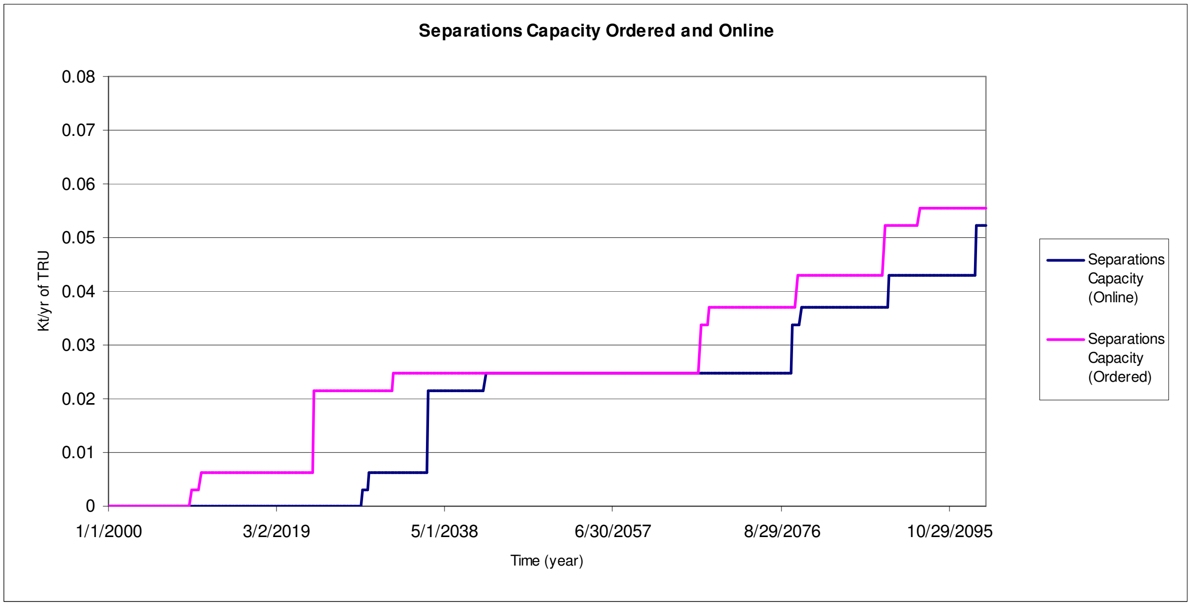

Figure 3-164: Separations Capacity with 9 Year Delay

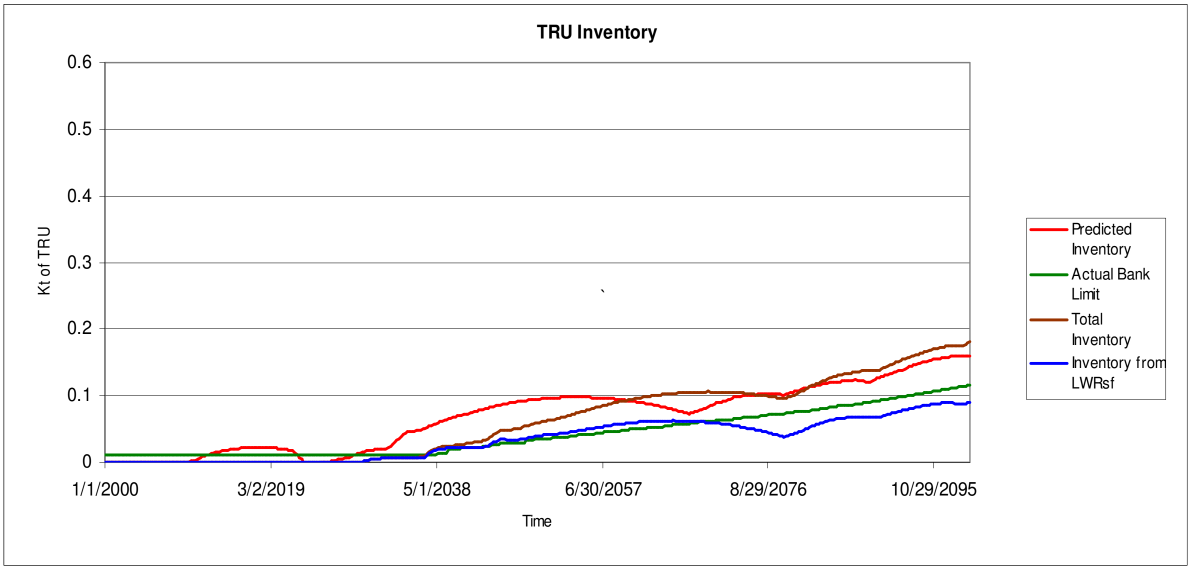

Figure 3-165: Inventory with 9 Year Delay

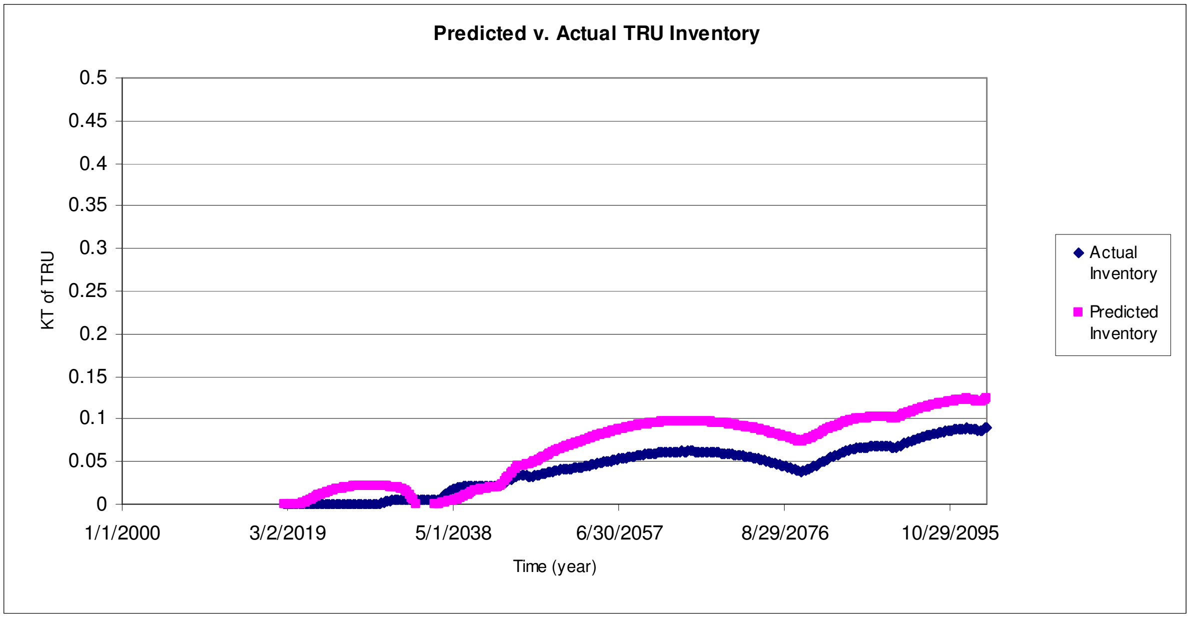

Figure 3-166: Predicted v. Actual Inventory with 9 Year Delay

<u>Scenario 3: Separation Facility Size of 0.5 Kt/yr with a 3 Year Lead Time and 10% FBR Growth</u>

This next scenario shows an increase in the lead time to 3 years, from the 1 year that was analyzed in the first case. The increased lead time further reduces the number of FBRs that are waiting for fuel to be delivered (Figure 3-167). The inventory in Figure 3-169 is also closer to the minimum bank limit.

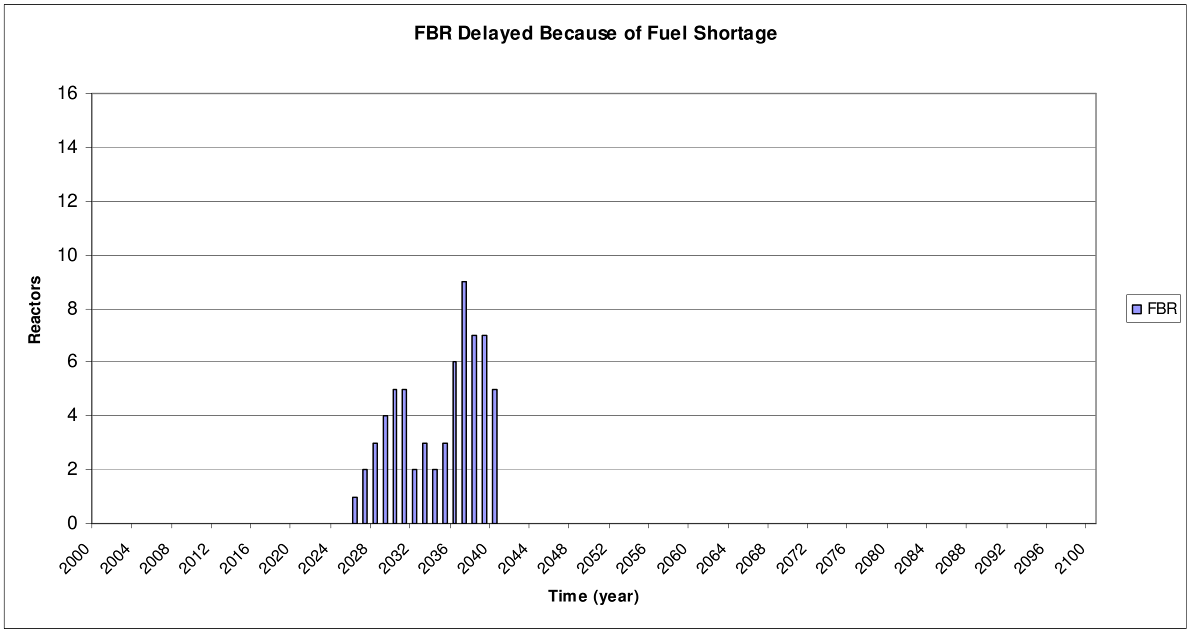

Figure 3-167: FBRs Delayed at Startup

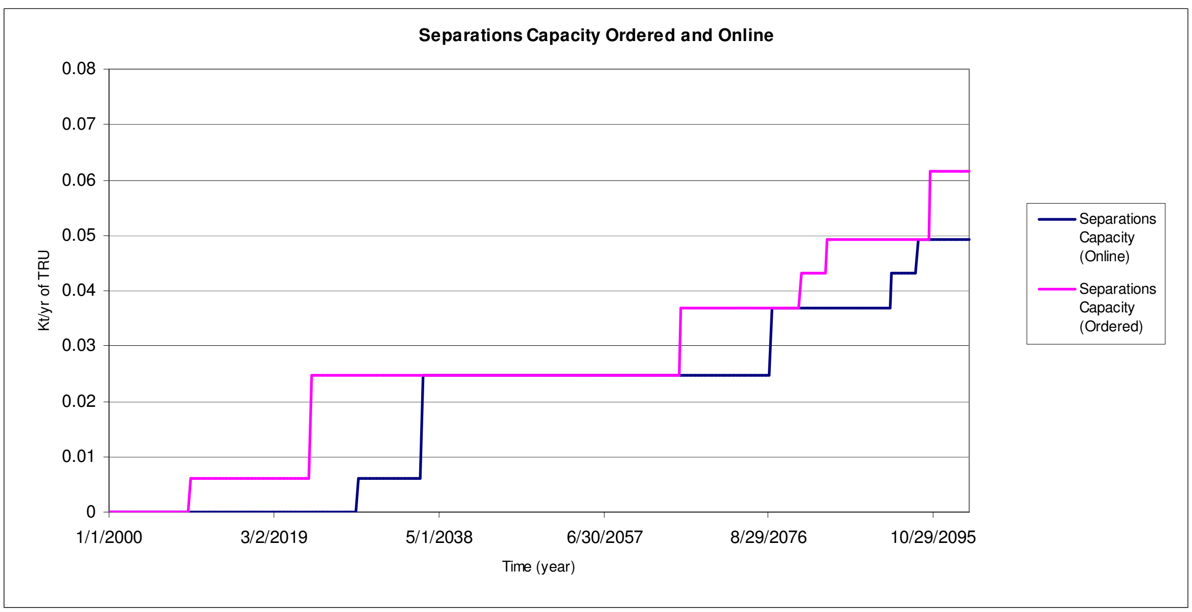

Figure 3-168: Separations Capacity with 9 Year Delay

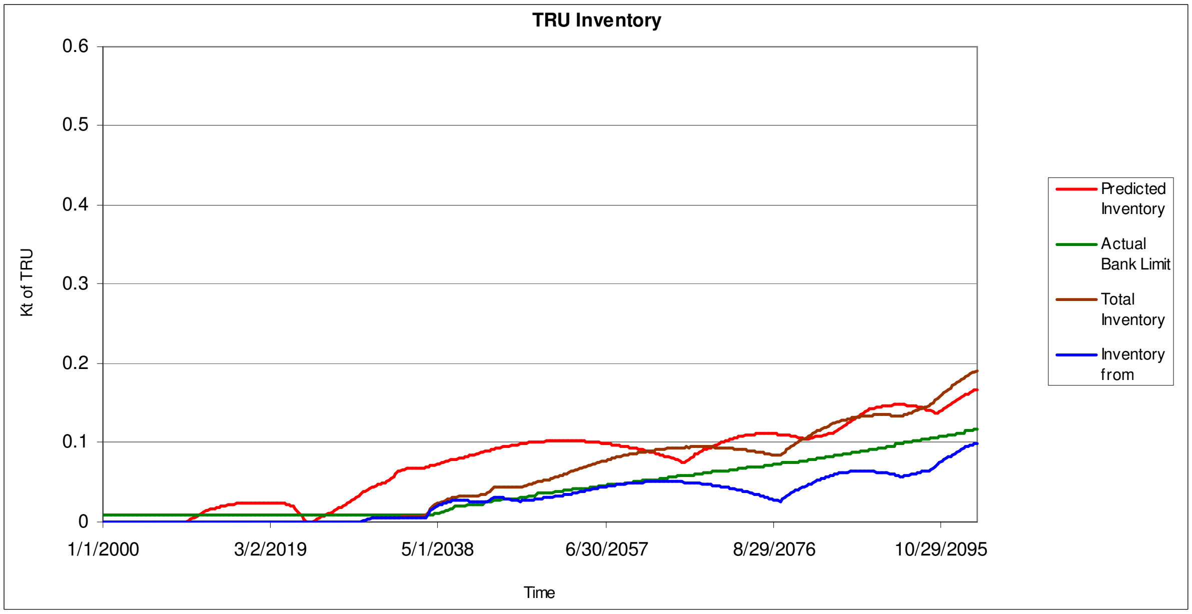

Figure 3-169: Inventory with 9 Year Delay

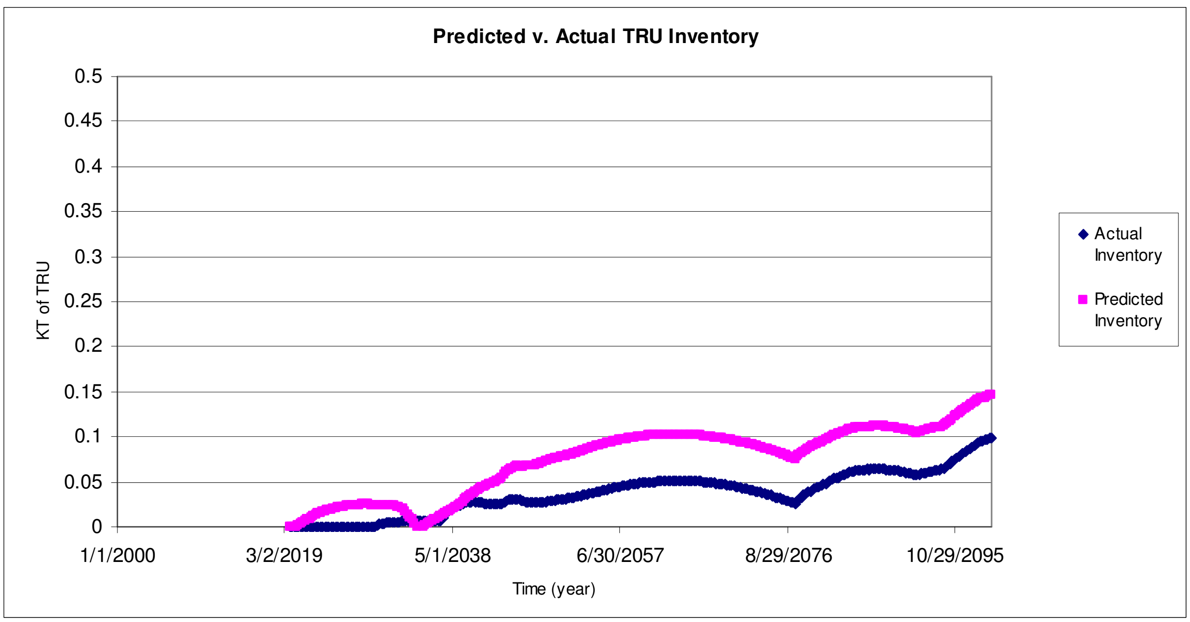

Figure 3-170: Predicted v. Actual Inventory with 9 Year Delay

3.3.1.2 New FBR Build Held at 20% of Energy Growth

The following results show the analysis of delaying the first separation facilities ordered by 9 year. Table 3-4 gives a summary of the scenarios with their respective lost FBR GWe values. This helps to show which case has the most negative affect from a delay in the construction of separation facilities. In the remainder of this section the graphs presented in Figure 3-171 - Figure 3-174, Figure 3-175 - Figure 3-178, Figure 3-179 - Figure 3-182, and Figure 3-183 - Figure 3-186 show the results for Scenario 1, Scenario 2, Scenario 3, and Scenario 4 of Table 3-4, respectively.

Table 3-4: Lost GWe Years for Separation Facility Delay with 20% FBR Growth

	20% FBR Growth		Lost FBR GWe Years
Scenario Number	Facility Size	Lead Time	
1	1 kt/yr	1 yr	26.64GWe-yr
2	0.5 kt/yr	4 yr	15.12GWe-yr
3	0.25 kt/yr	5 yr	8.64GWe-yr
4	0.25 kt/yr	7 yr	2.88GWe-yr

__Scenario 1: Separation Facility Size of 1 Kt/yr with a 1 Year Lead Time and 20% FBR Growth__

In this scenario the inventory of TRU at the beginning of the simulation is significantly less than the expected level (Figure 3-174). This causes the large number of FBRs waiting without startup fuel, as shows in Figure 3-171.

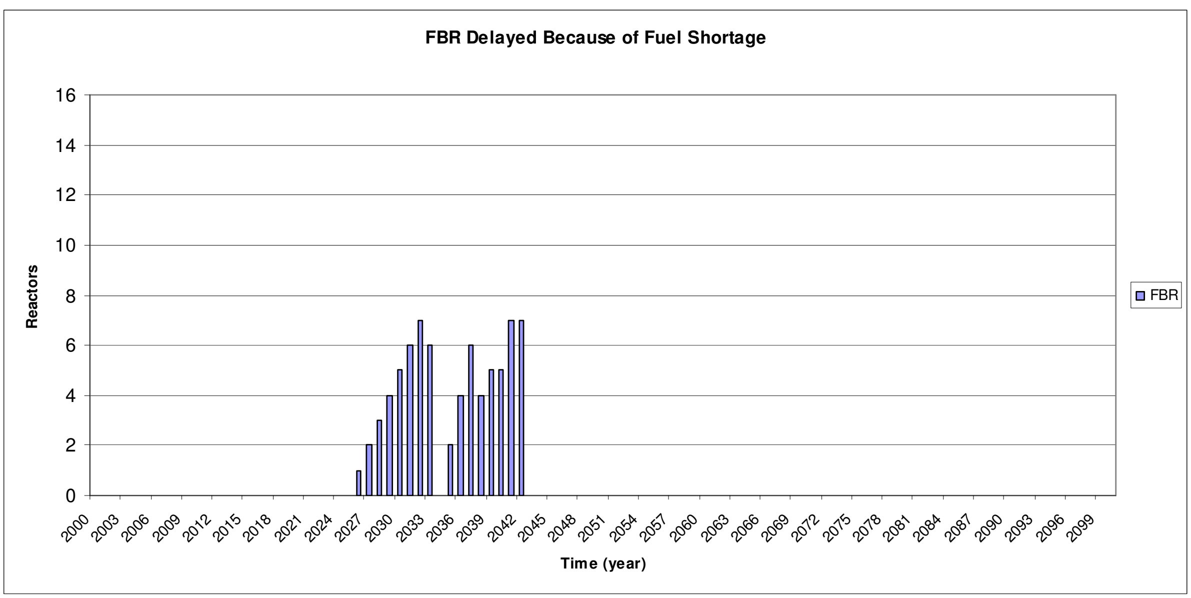

Figure 3-171: FBRs Waiting to Startup

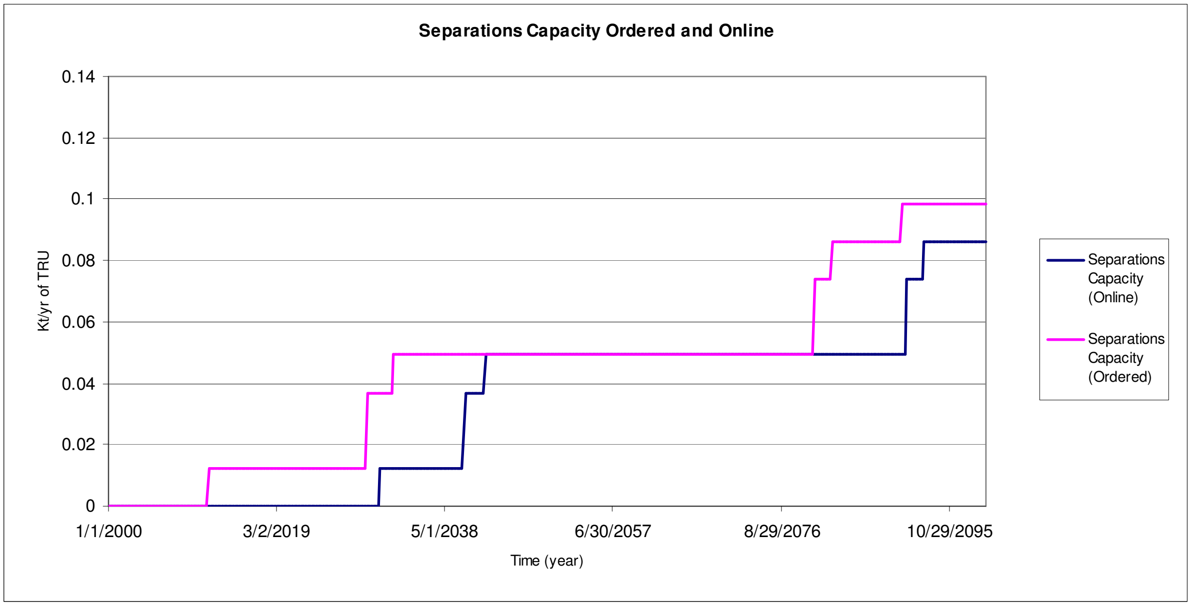

Figure 3-172: Separations Capacity with 9 Year Delay

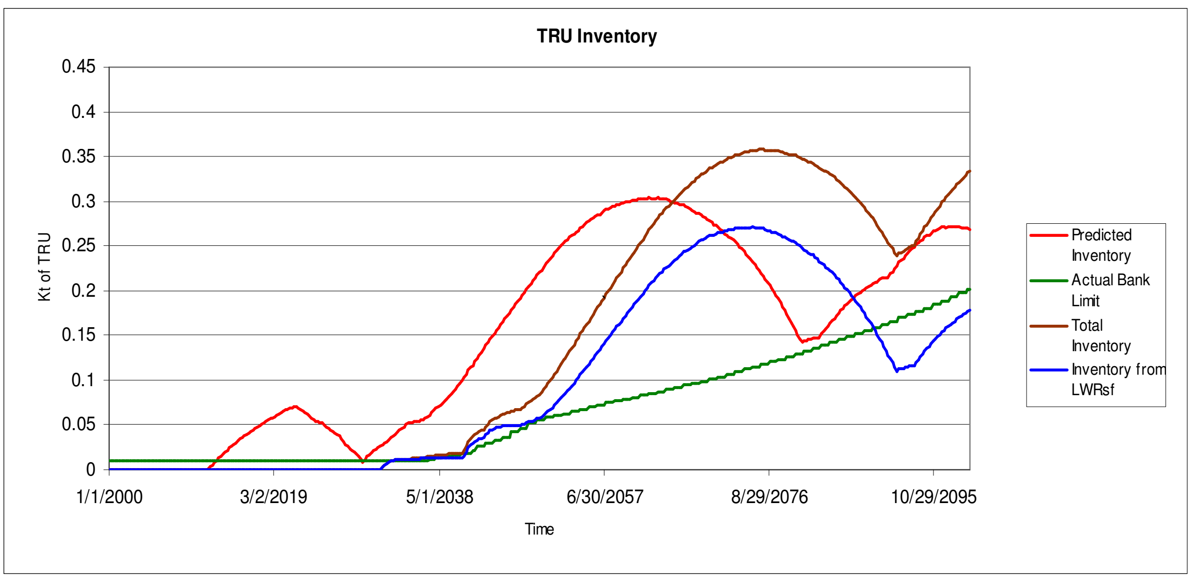

Figure 3-173: Inventory with 9 Year Delay

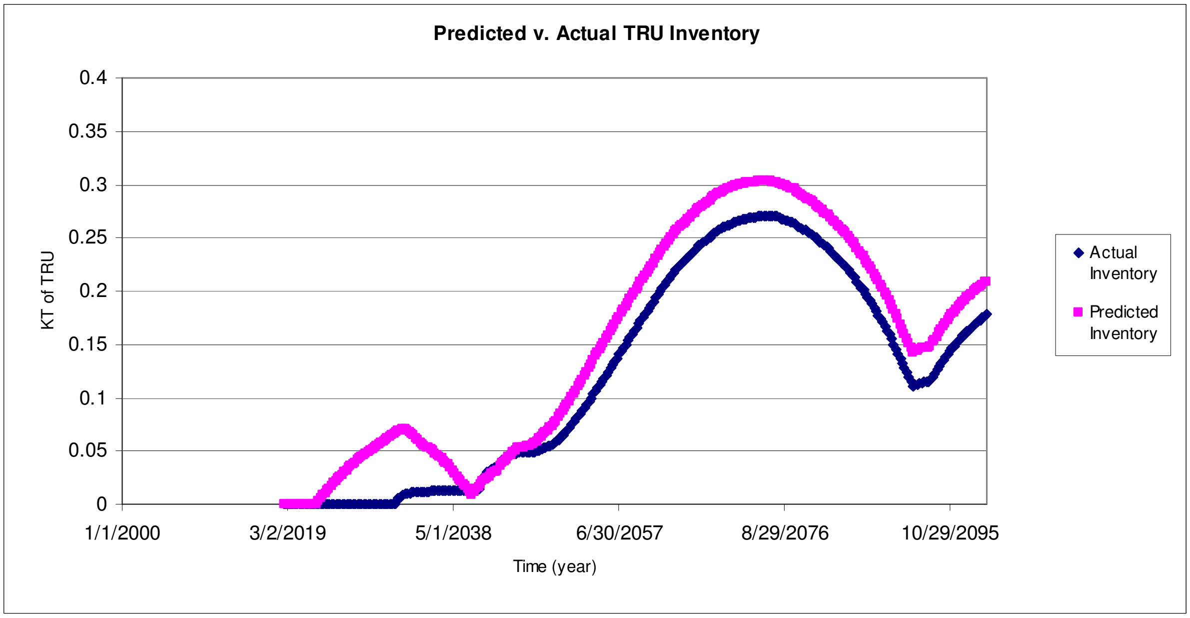

Figure 3-174: Predicted v. Actual Inventory with 9 Year Delay

Scenario 2: Separation Facility Size of 0.5 kt/yr with Lead Time of 4 years and 20% FBR Growth

Decreasing the separation facility size and increasing the lead time helps to reduce the number of FBRs waiting for a startup batch (Figure 3-175). The reason for this is because the increased lead time brings facilities online earlier because they are ordered earlier. This can be seen by comparing the startup time of the separation capacity in Figure 3-172 and Figure 3-176. This scenario is able to recover quicker and predict an accurate inventory level that operates above the bank limit (Figure 3-177 and Figure 3-178).

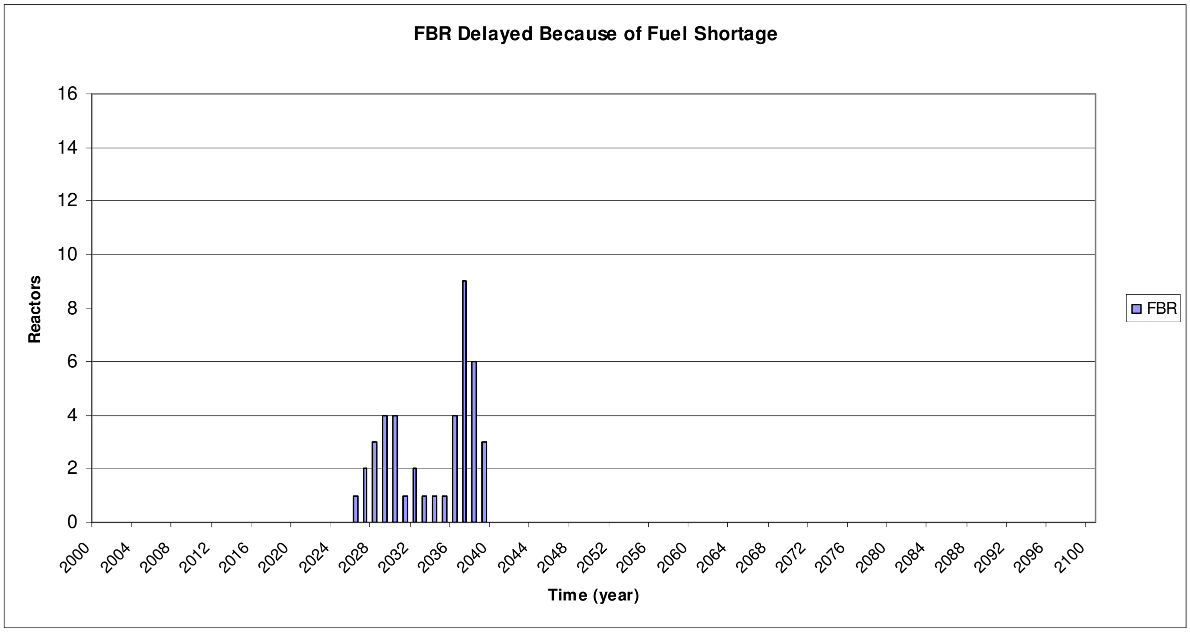

Figure 3-175: Reactors Waiting to Startup

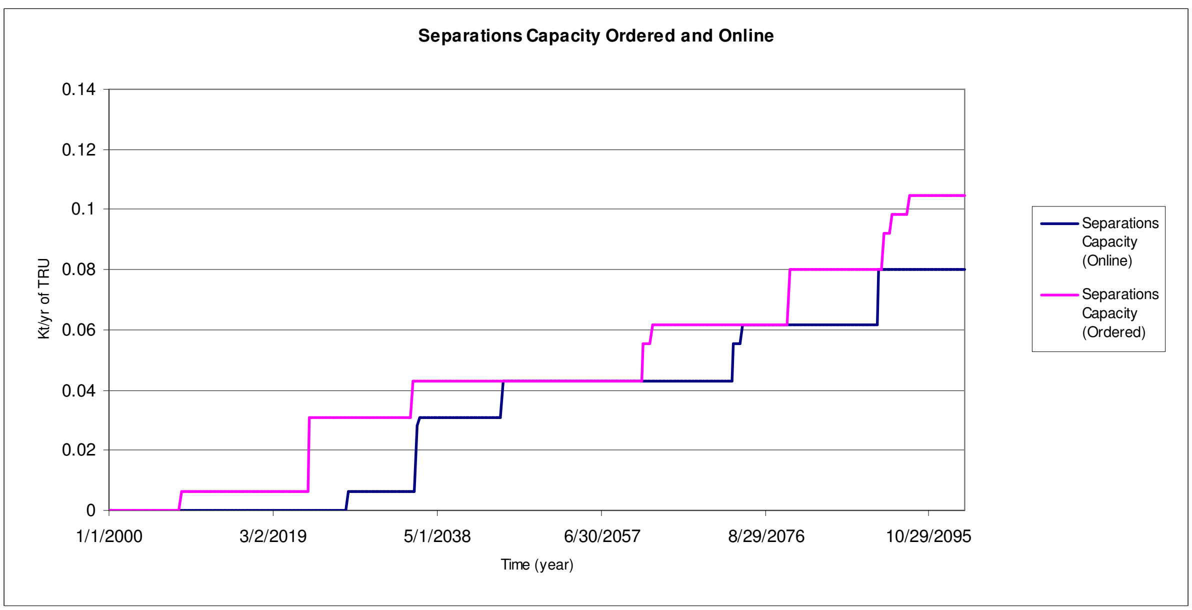

Figure 3-176: Separations Capacity with 9 Year Delay

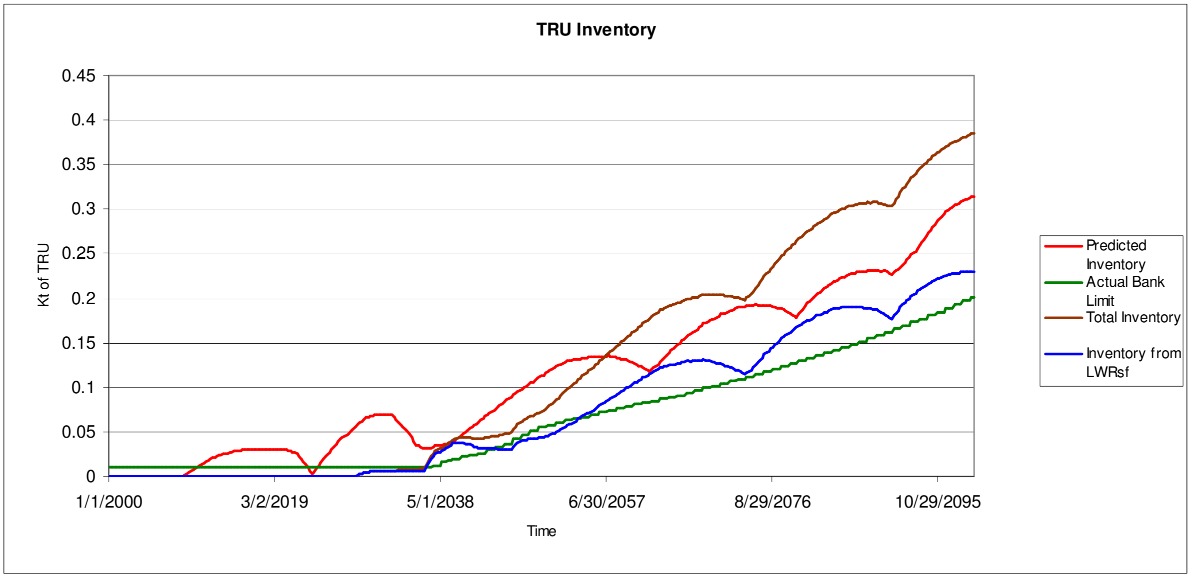

Figure 3-177: Inventory with 9 Year Delay

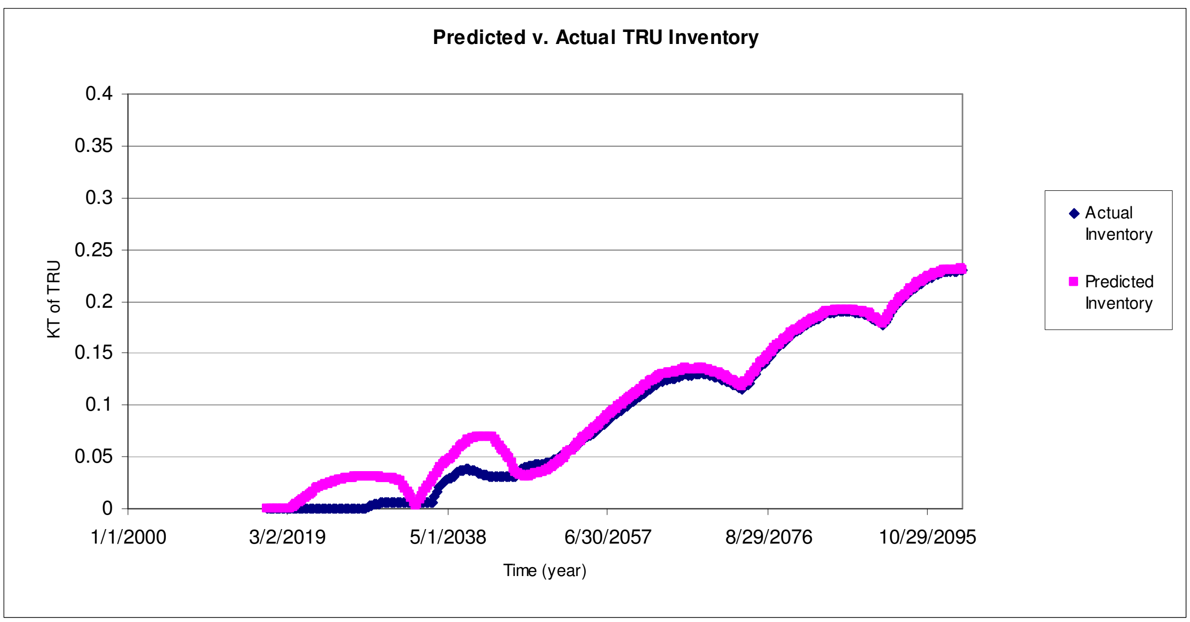

Figure 3-178: Predicted v. Actual Inventory with 9 Year Delay

Scenario 3: Separation Facility Size of 0.25 kt/yr with a Lead Time of 5 Years and 20% FBR Growth

In this next scenario, increasing the lead time and decreasing the separation facility size helps to further decrease the number of reactors waiting for startup fuel (Figure 3-179), while also allowing the model to predict an accurate inventory (Figure 3-182).

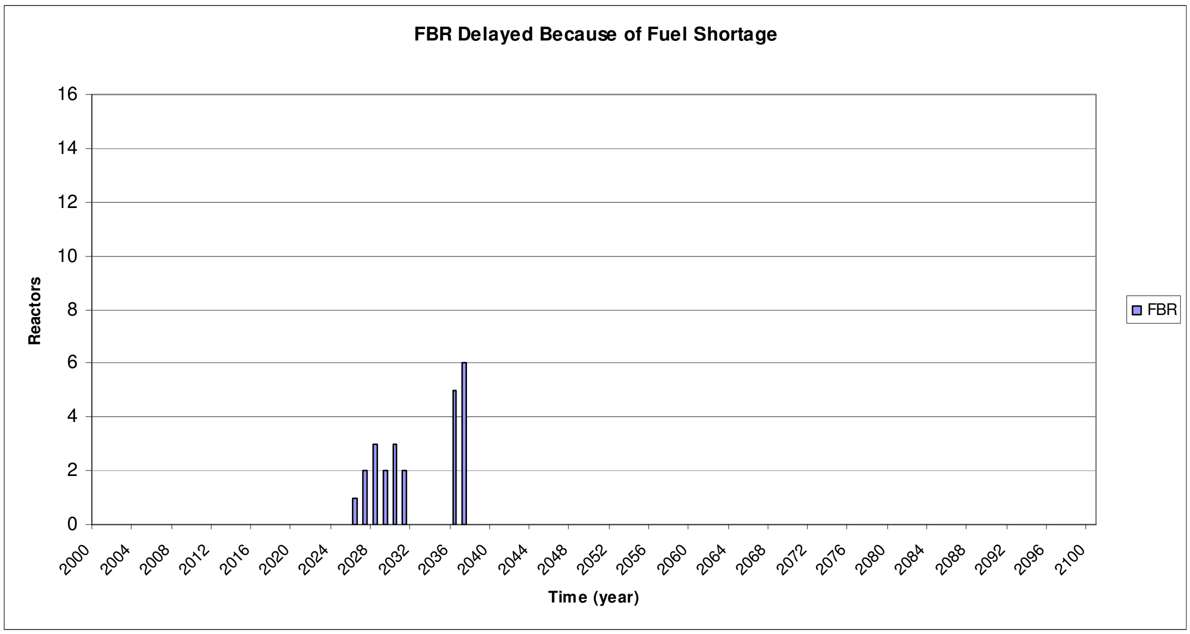

Figure 3-179: Reactors Waiting to Startup

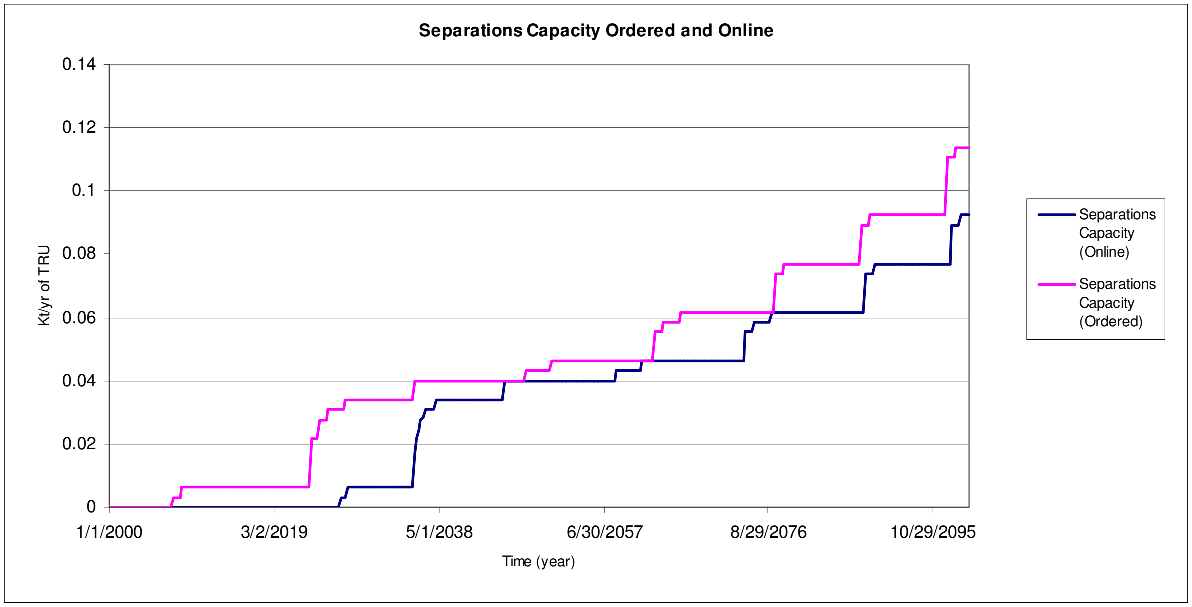

Figure 3-180: Separations Capacity with 9 Year Delay

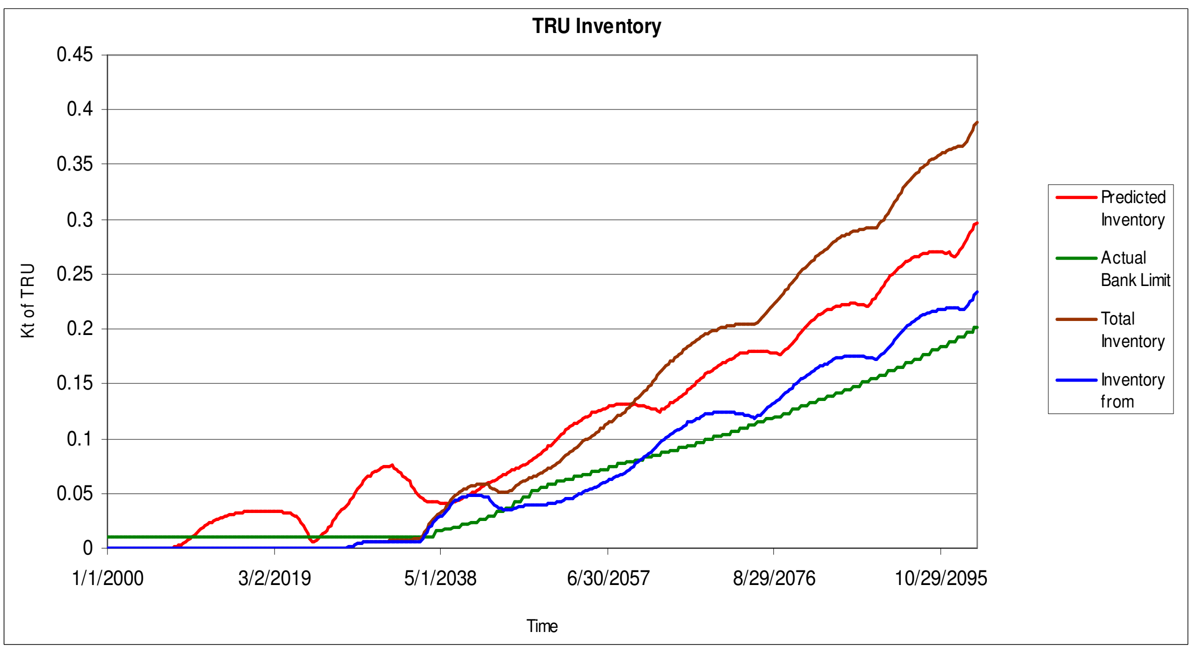

Figure 3-181: Inventory with 9 Year Delay

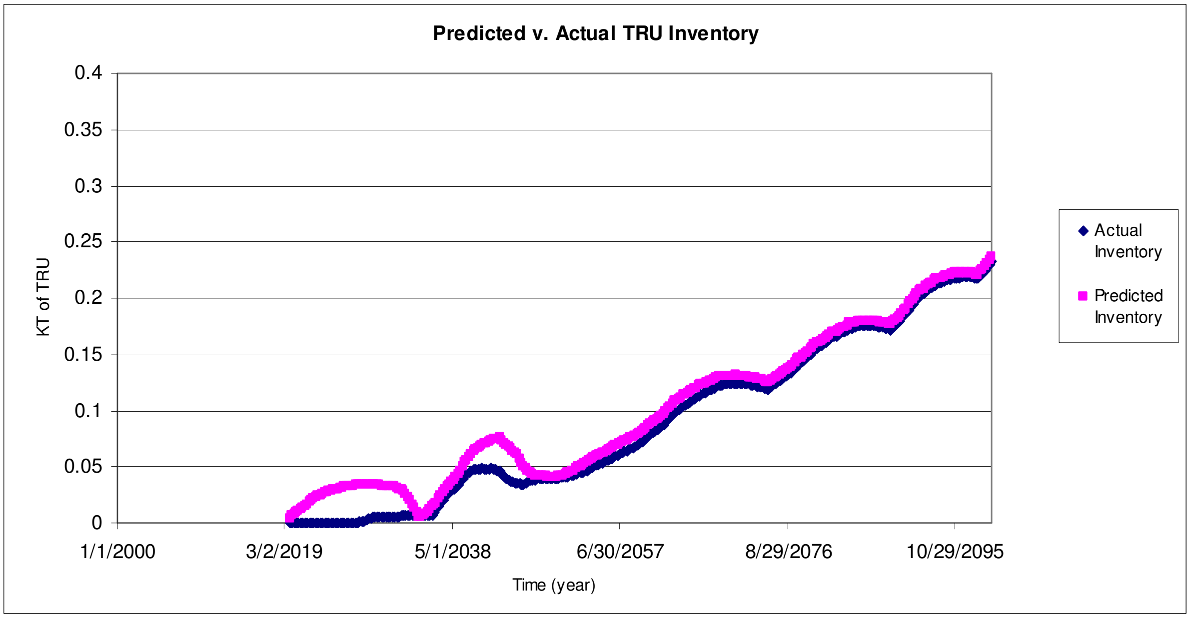

Figure 3-182: Predicted v. Actual Inventory with 9 Year Delay

<u>Scenario 4: Separation Facility Size of 0.25 kt/yr with a Lead Time of 7 Years and 20% FBR Growth</u>

Everything in the previous scenario was held constant and the lead time was increased to 7 years. This did bring down the number of FBRs waiting for startup fuel (Figure 3-183) and decreased the lost FBR GWe.

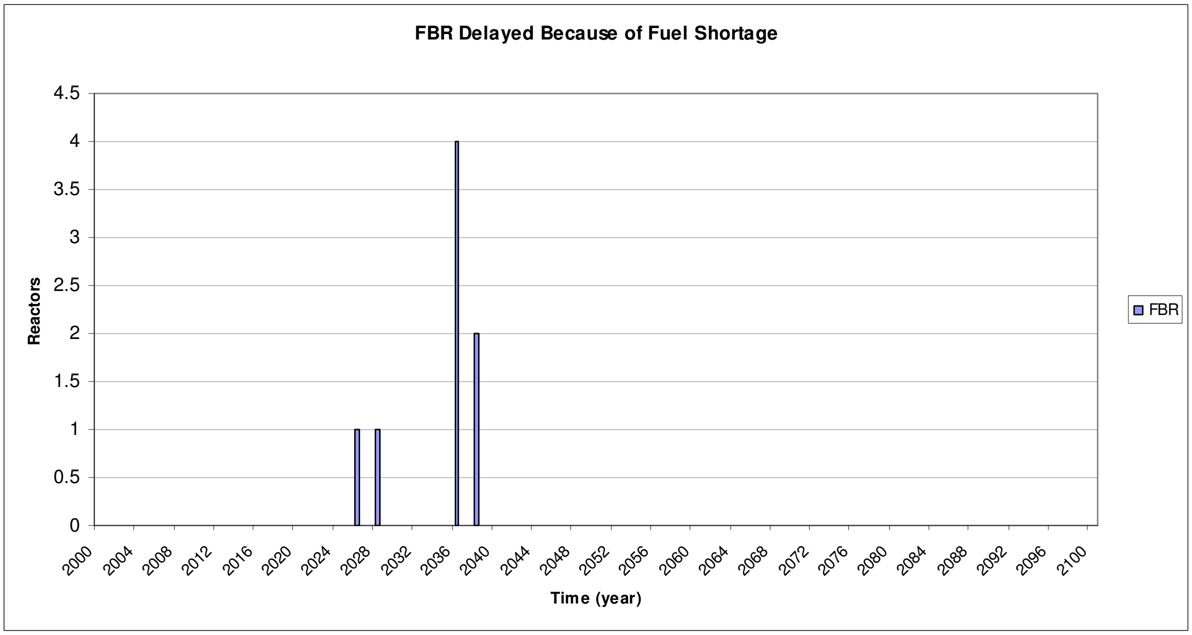

Figure 3-183: Reactors Waiting to Startup

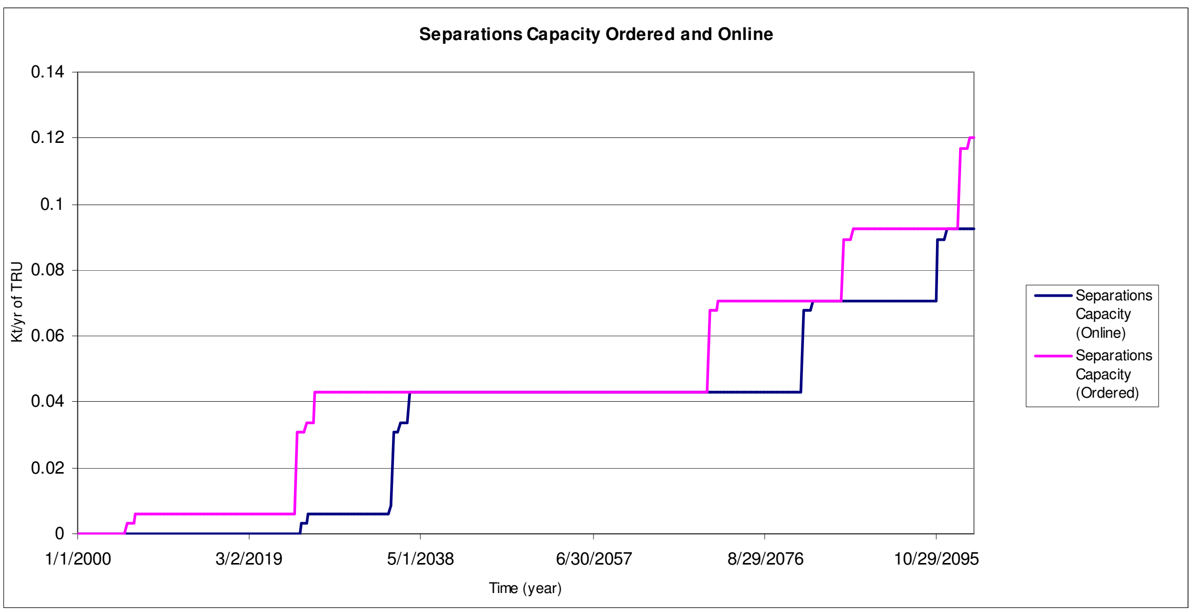

Figure 3-184: Separations Capacity with 9 Year Delay

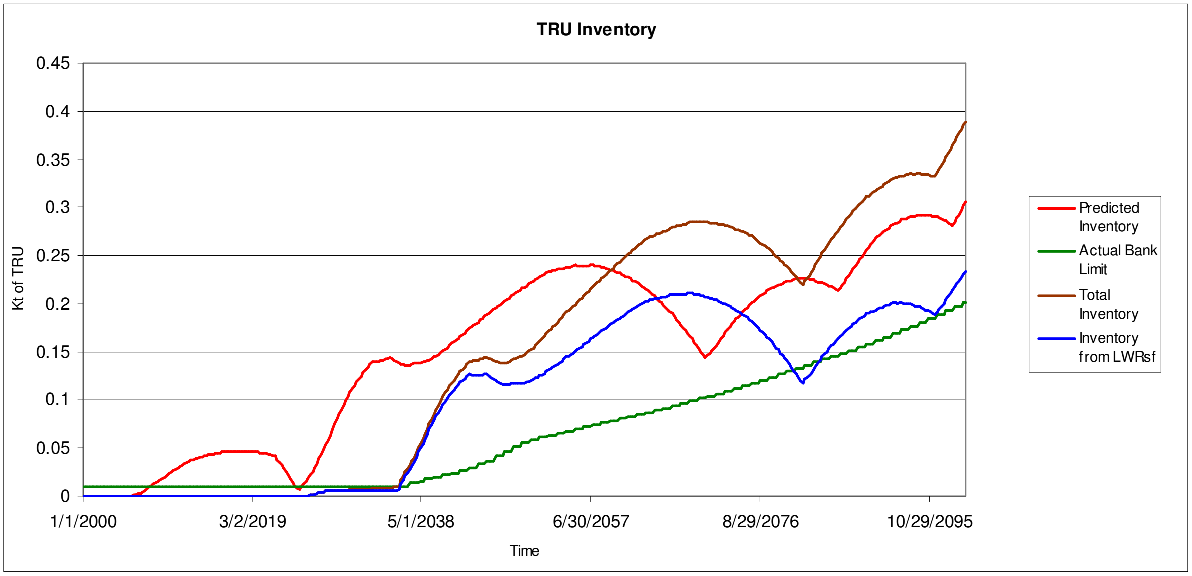

Figure 3-185: Inventory with 9 Year Delay

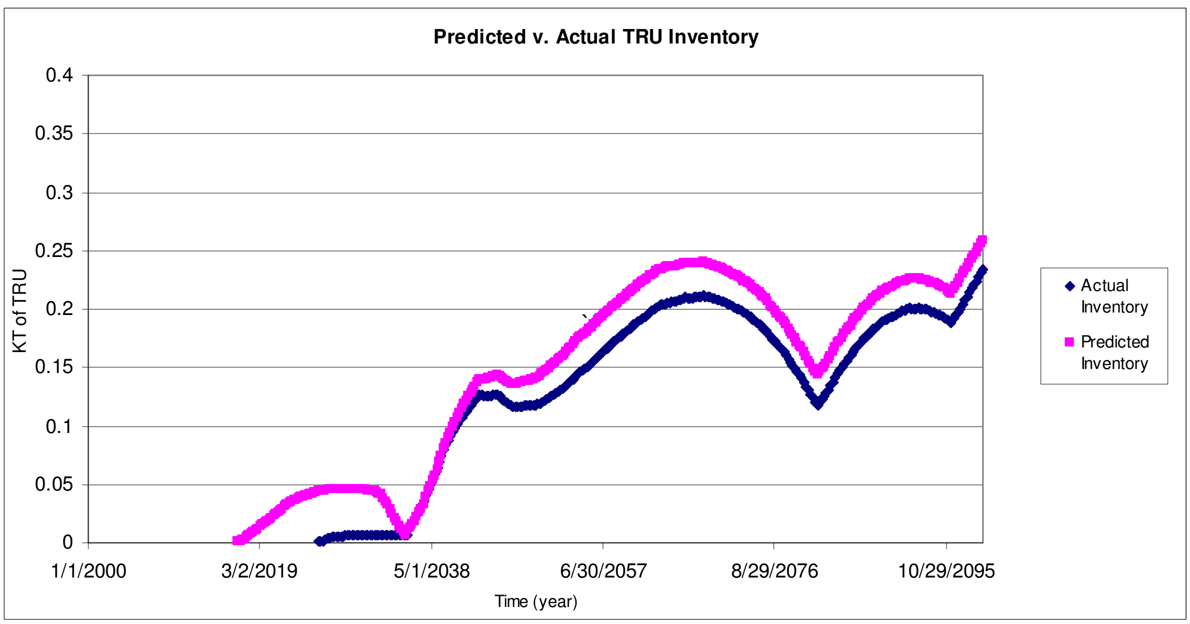

Figure 3-186: Predicted v. Actual Inventory with 9 Year Delay

3.3.1.3 New FBR Ramped up to 100% of Growth Rate or Max Value

The data presented in Table 3-5 shows a summary of the scenarios that will be run for a FBR growth rate of 100%. This table also shows the lost FBR GWe years due to separation facilities not starting up on time. In the next three scenarios the number of reactors that are waiting for startup fuel decreases significantly than the scenarios with the 10% and 20% reactor growth rate. The reason behind this is because the separations capacity build rate, after the first facility starts up, dramatically increases (Figure 3-188, Figure 3-192 and Figure 3-196). These scenarios are not representative of a real world simulation because of the rapid build rate. The graphs shown in Figure 3-187 - Figure 3-190, Figure 3-191 - Figure 3-194, and Figure 3-195 - Figure 3-198 are the results for Scenario 1, Scenario 2, and Scenario 3 in Table 3-5, respectively.

Table 3-5: Lost GWe Years for Separation Facility Delay with 100% FBR Growth

	100% FBR Growth		Lost FBR GWe Years
Scenario Number	**Facility Size**	**Lead Time**	
1	0.5 kt/yr	7 yr	2.88GWe-yr
2	0.25 kt/yr	7 yr	2.88GWe-yr
3	0.25 kt/yr	5 yr	10.44GWe-yr

Scenario 1: Separations Facility Size of 0.5 kt/yr with a 7 Year Lead Time and 100% FBR Growth

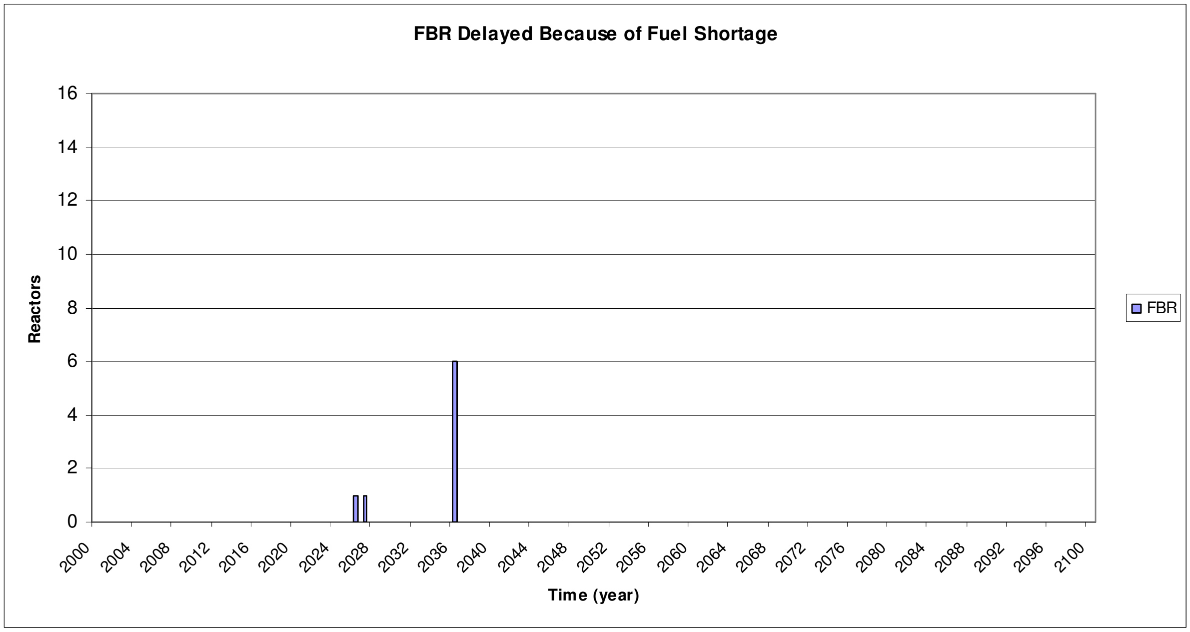

Figure 3-187: FBRs Waiting to Startup

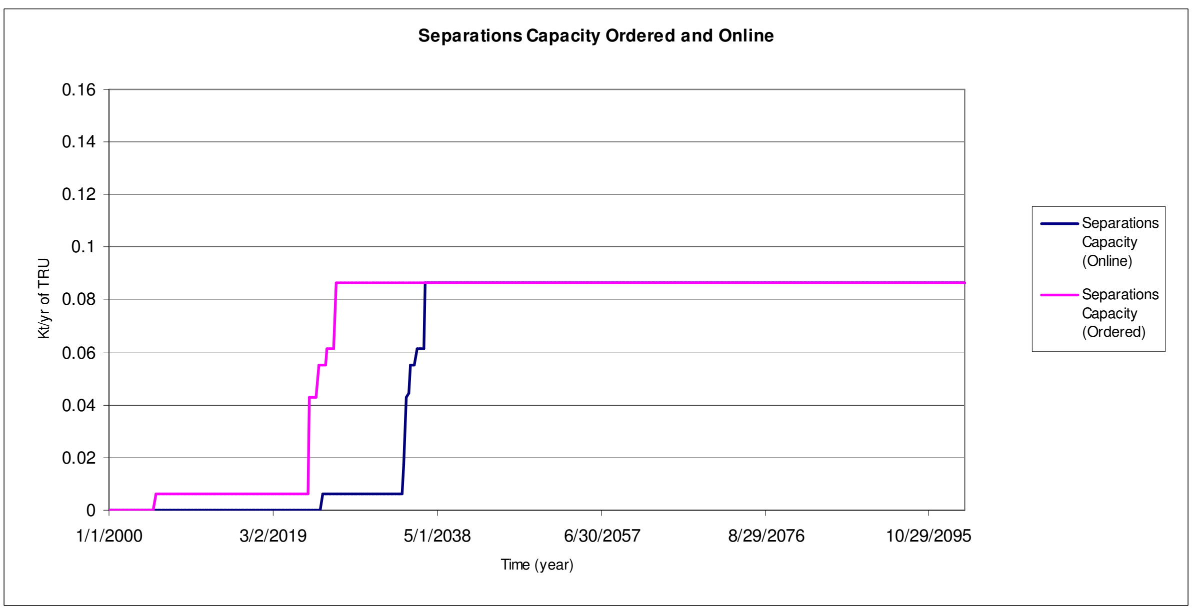

Figure 3-188: Separations Capacity with 9 Year Separations Delay

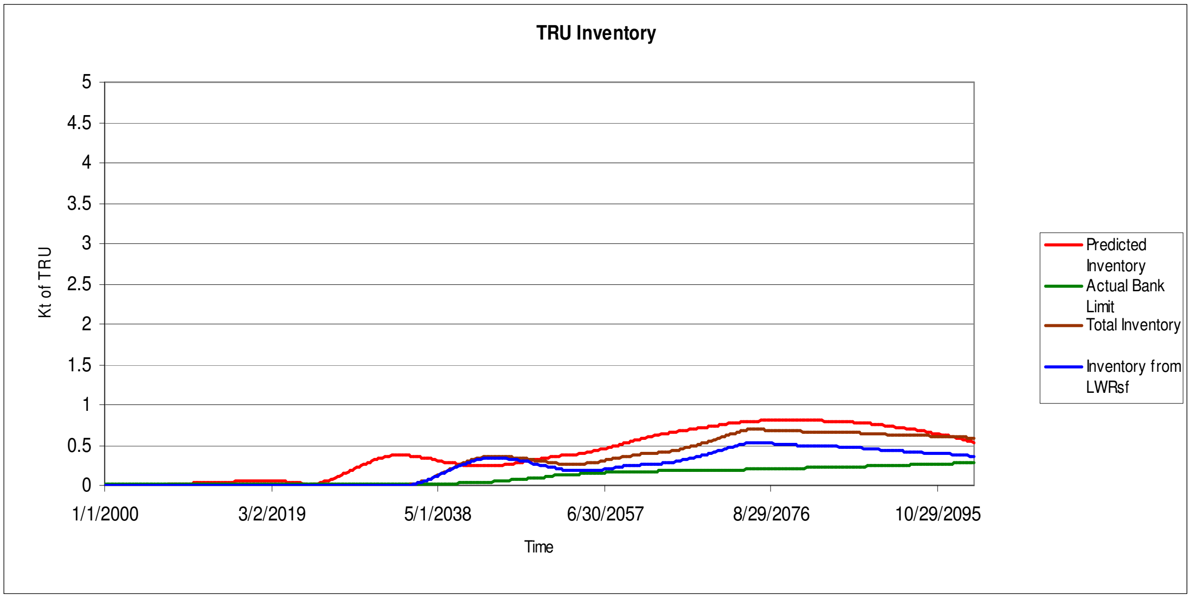

Figure 3-189: Inventory with 9 Year Separation Delay

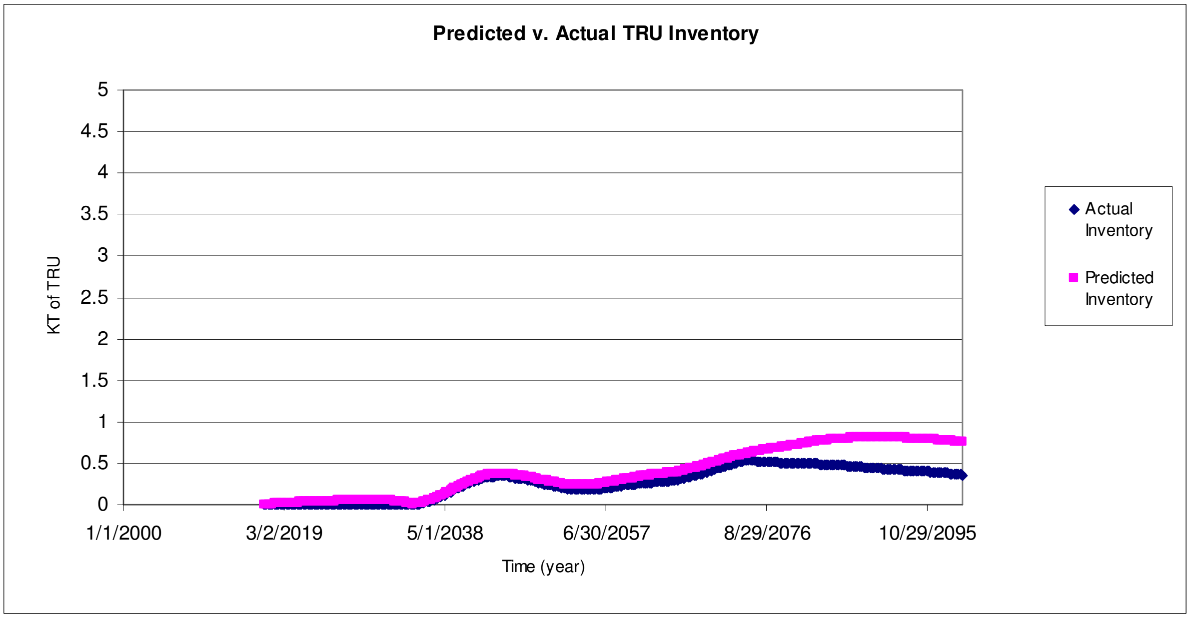

Figure 3-190: Predicted v. Actual Inventory with 9 Year Delay

Scenario 2: Separation Facility Size of 0.25 kt/yr with a 7 year Lead Time and 100% FBR Growth

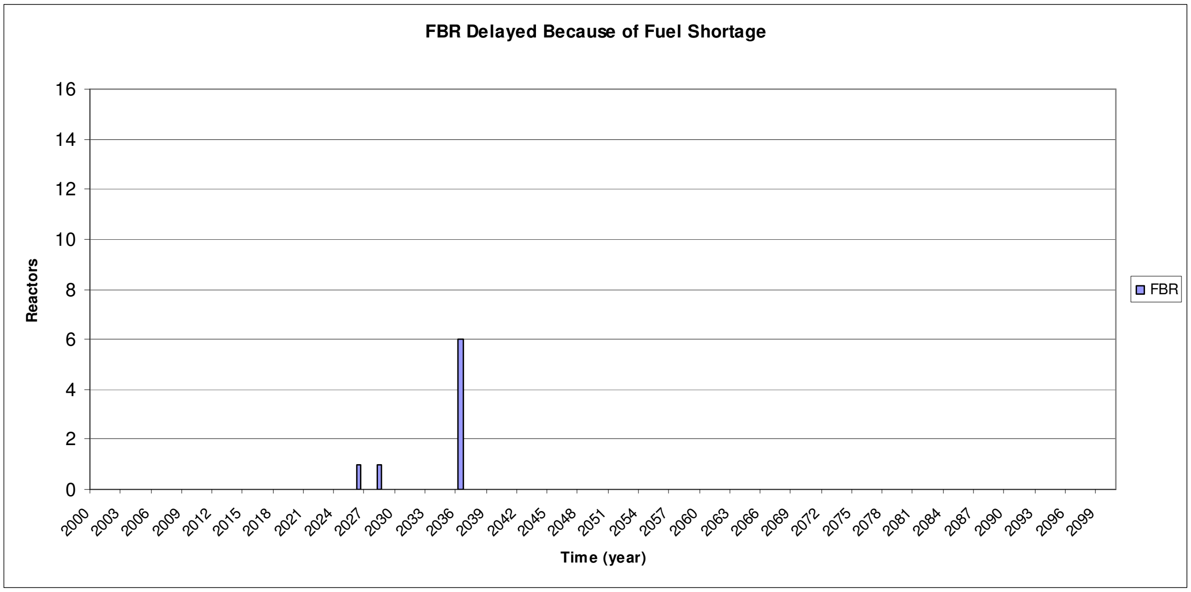

Figure 3-191: Reactors Waiting to Startup

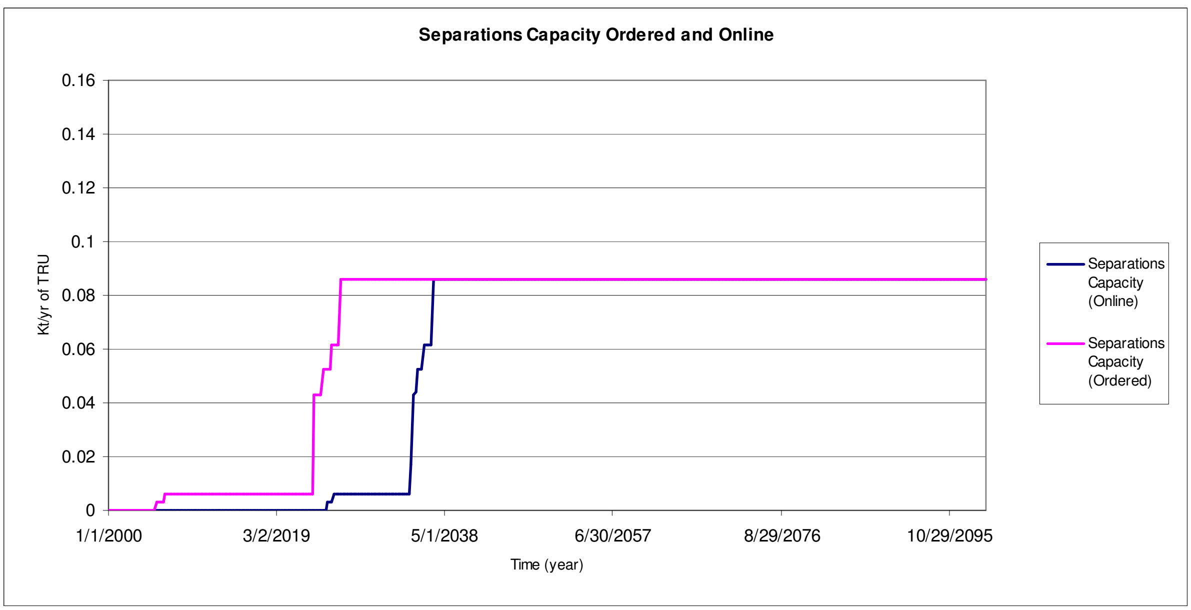

Figure 3-192: Separations Capacity with 9 Year Delay

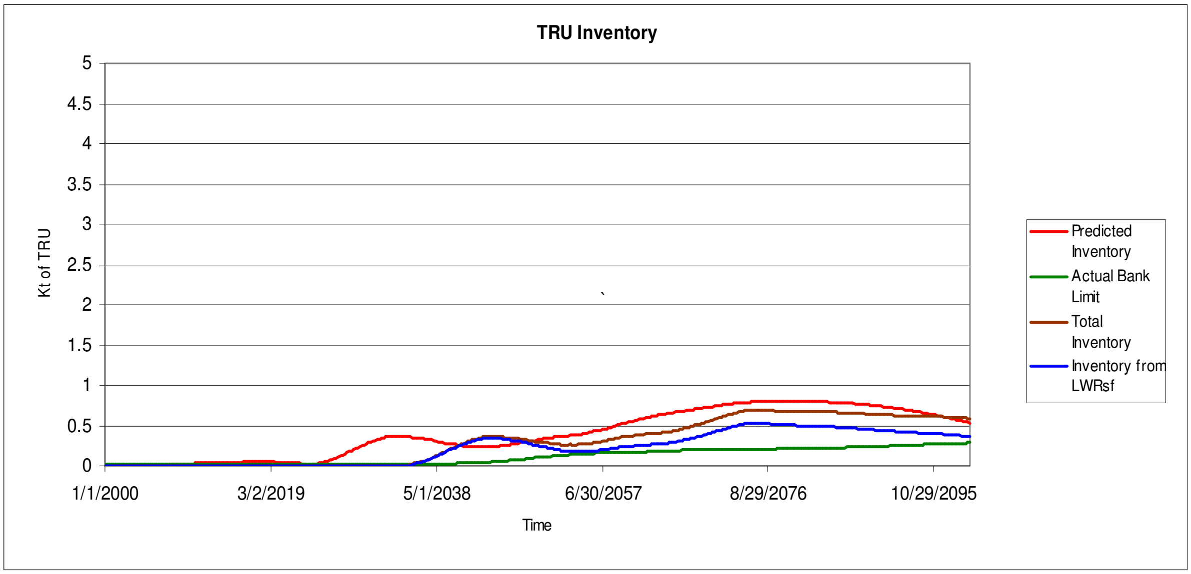

Figure 3-193: Inventory with 9 Year Delay

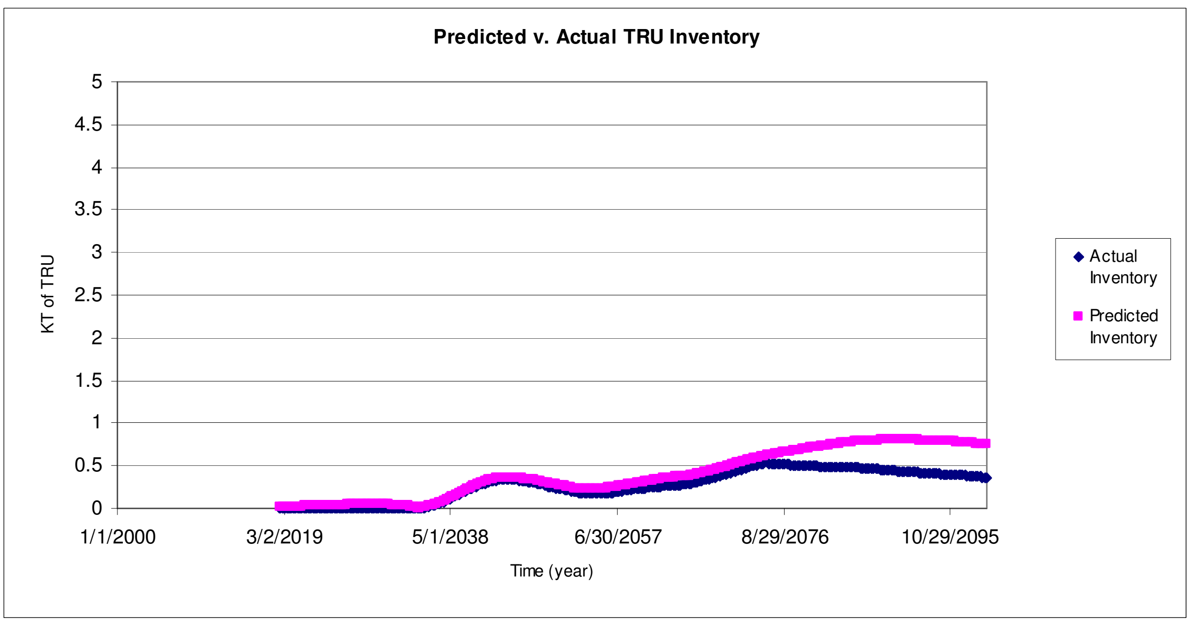

Figure 3-194: Predicted v. Actual Inventory with 9 Year Delay

Scenario 3: Separation Facility Size of 0.25 kt/yr with a 5 year Lead Time and 100% FBR Growth

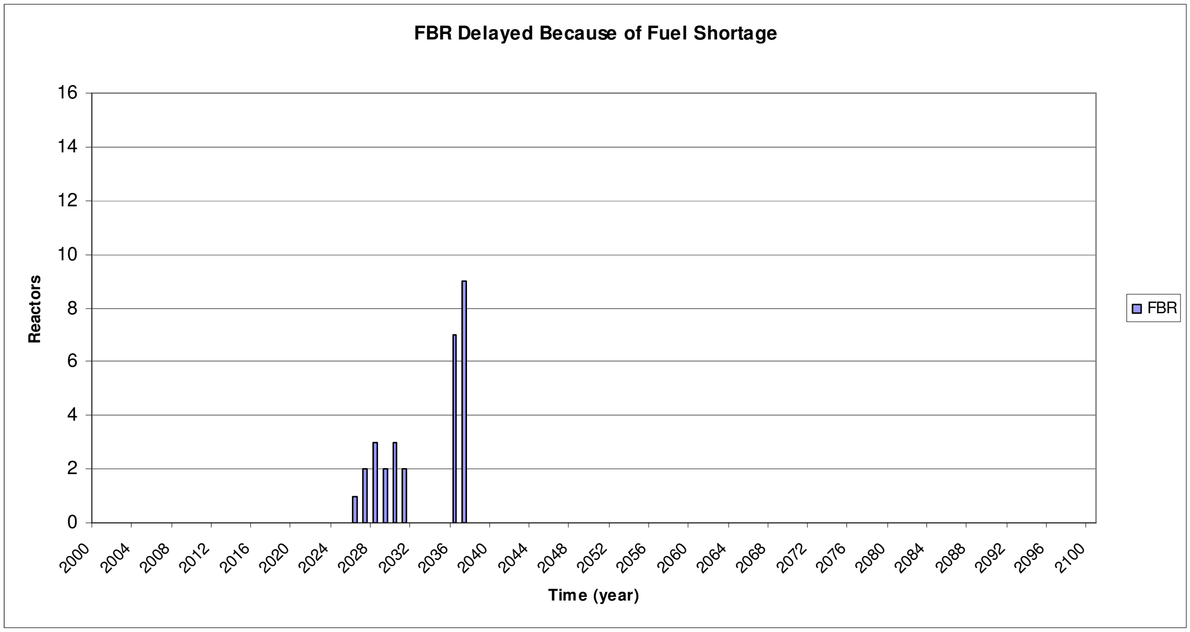

Figure 3-195: Reactors Waiting to Startup

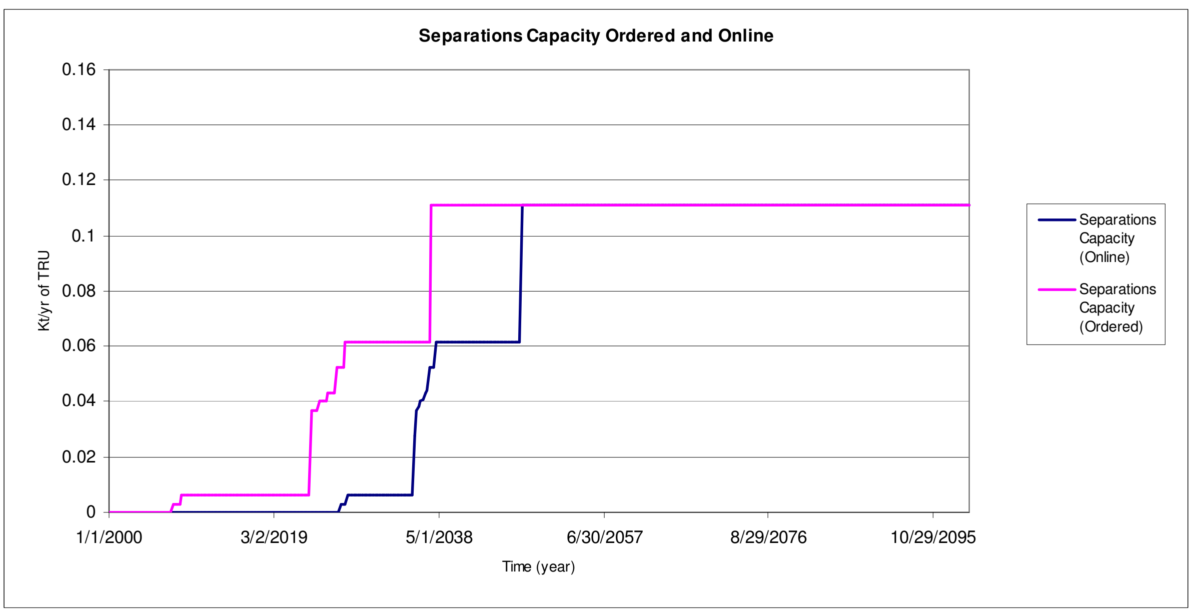

Figure 3-196: Separations Capacity with 9 Year Delay

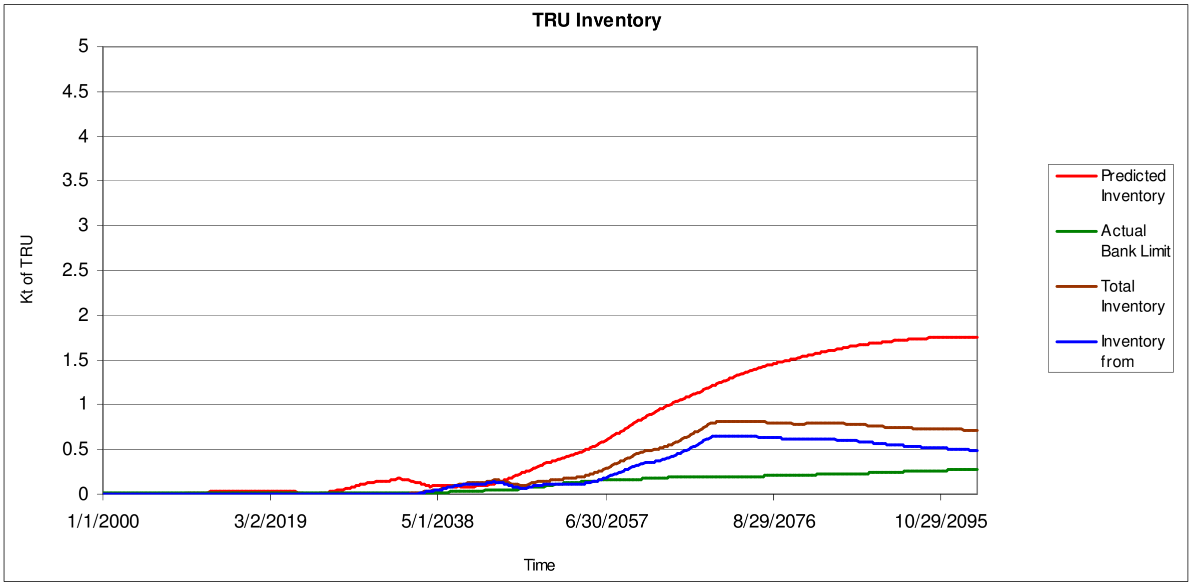

Figure 3-197: Inventory with 9 Year Delay

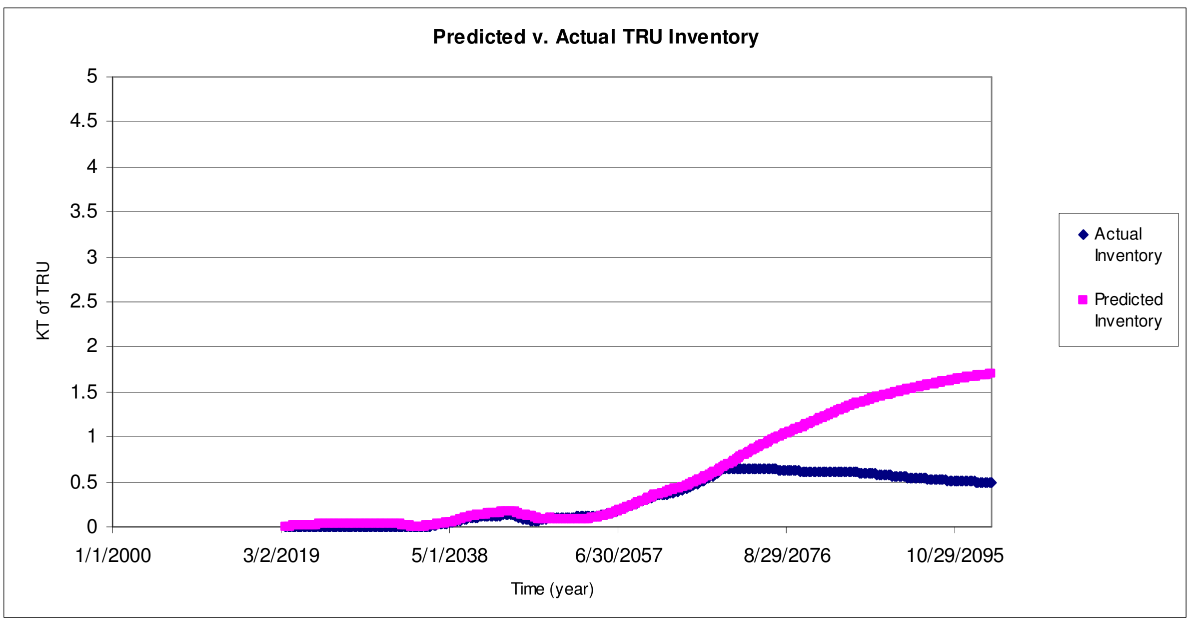

Figure 3-198: Predicted v. Actual Inventory with 9 Year Delay

3.3.1.4 Summary of Separation Facility Delay

Overall increasing the lead time for building separation facilities helps to mitigate the negative consequences of a delay in the construction of a separation facility. This can be seen by noting the decrease in the lost FBR GWe-yr as the lead times were increased. Comparing the scenarios in Table 3-3, show that increasing the lead time has a greater affect than increasing the separation facility size. In Table 3-3 Scenarios 2 and 3 are identical except Scenario 2 has a separation facility size of 0.25 kt/yr and Scenario 3 has a separation facility size of 0.5 kt/yr. The difference between the lost FBR GWe-yr due to increasing from 0.25 kt/yr to 0.5 kt/yr is only a total of 2.52GWe-yr. In comparing Scenario 1 with Scenario 2, the separation facility size is constant at 0.5 kt/y while the lead time increases from 1 to 3. This creates a decrease in the GWe-yr of 12.24GWe-yr, which is significantly larger. Table 3-4 shows a similar trend for increasing the lead time on separation facilities. The scenarios with the 100% reactor growth rate, shown in Table 3-5, produced relatively small lost FBR GWe-yr; however, their build schedule is not very realistic because of the large build rate paired with a long period of no new separations capacity.

3.3.2 One Separation Facility Taken Offline for Several Years

In the next group of scenarios the first separation facility to come online is allowed to operate for 5 years and then is taken offline for the next 5 years. This upset scenario will simulate the Thorp Separation facility being completely shutdown and then restarted.

3.3.2.1 New FBR Build Held at 10% of Growth

Table 3-6 shows the scenarios that will be analyzed with bringing one separation facility offline. These scenarios are the optimal scenarios that were found in Section 3.2. Two additional scenarios were added in order to see the affects of increasing lead time for a given separation facility size. The graphs presented in Figure 3-199 - Figure 3-202, Figure 3-203 - Figure 3-205, Figure 3-206 - Figure 3-208, and Figure 3-209 - Figure 3-212 are the output results for Scenarios 1, 2, 3, and 4 in Table 3-6, respectively.

Table 3-6: Scenarios for Taking 1 Separation Facility Offline with 10% FBR Growth

Scenario	Separation Facility Size	Lead Time	Years Offline	Lost FBR GWe Years
1	0.5 kt/yr	1 yr	2027 – 2031	1.08GWe-yr
2	0.25 kt/yr	3 yr	2025 – 2029	0GWe-yr
3	0.5 kt/yr	3 yr	2025 – 2029	0GWe-yr
4	0.5 kt/yr	5 yr	2023 - 2027	0.72GWe-yr

Scenario 1: Separation Facility Size of 0.5 kt/yr with a 1 Year Lead Time and 10% FBR Growth

1 Separation Facility Offline between 2027 and 2031

In this scenario one separation facility goes offline after being online for 5 years and then remains offline for another 5 years. One facility goes offline starting in year 2027 and comes back online starting in year 2032, for a total of 5 years of being offline. The following graphs show the result of this simulation. Figure 3-200 shows the separations capacity working and then completely offline for the 5 years. The plot of the FBRs waiting for startup fuel is shown in Figure 3-199. There is only a small decrease in the actual inventory compared to the predicted inventory (Figure 3-202) because the nominal case (Figure 3-44) has a very small initial inventory due to the short lead time.

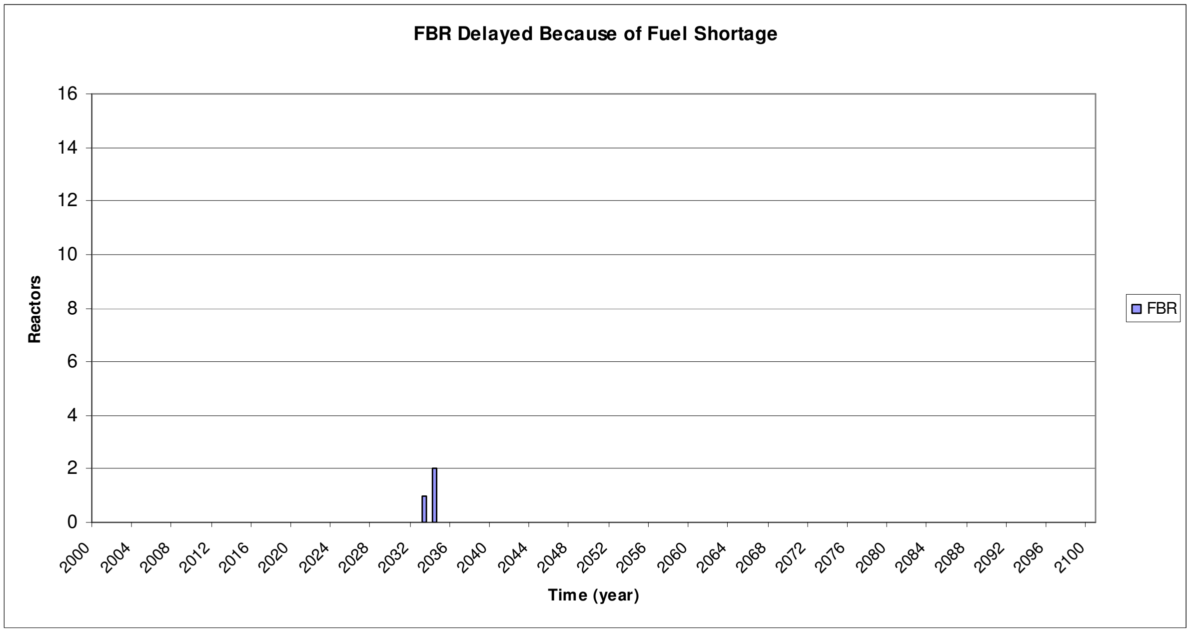

Figure 3-199: FBRs Waiting to Startup

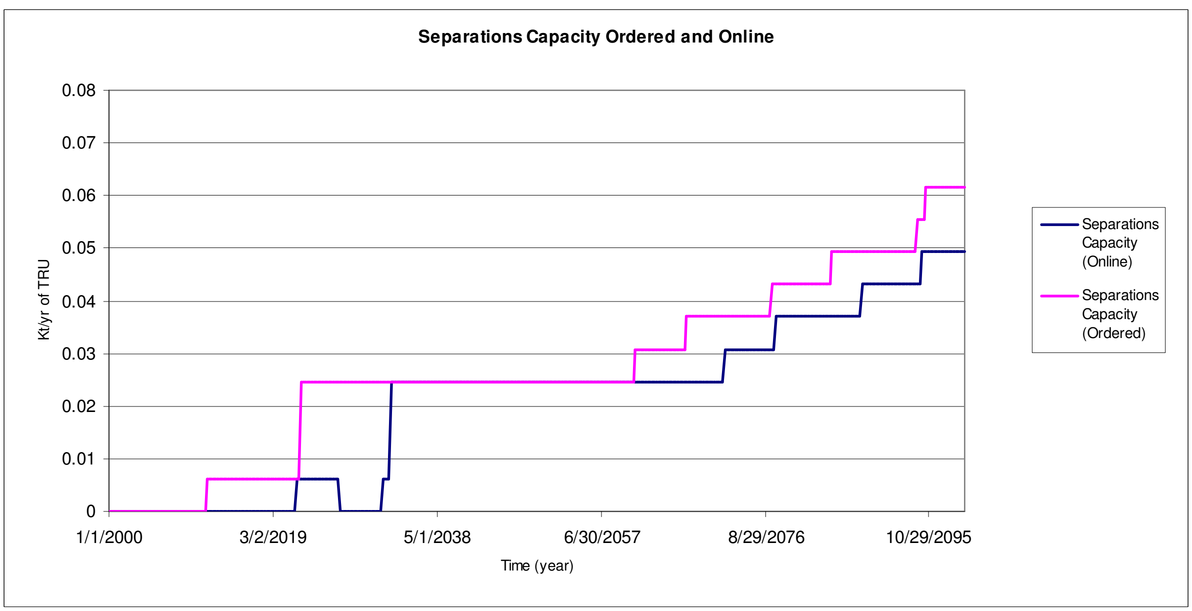

Figure 3-200: Separations Capacity with 1 Separation Facility Offline

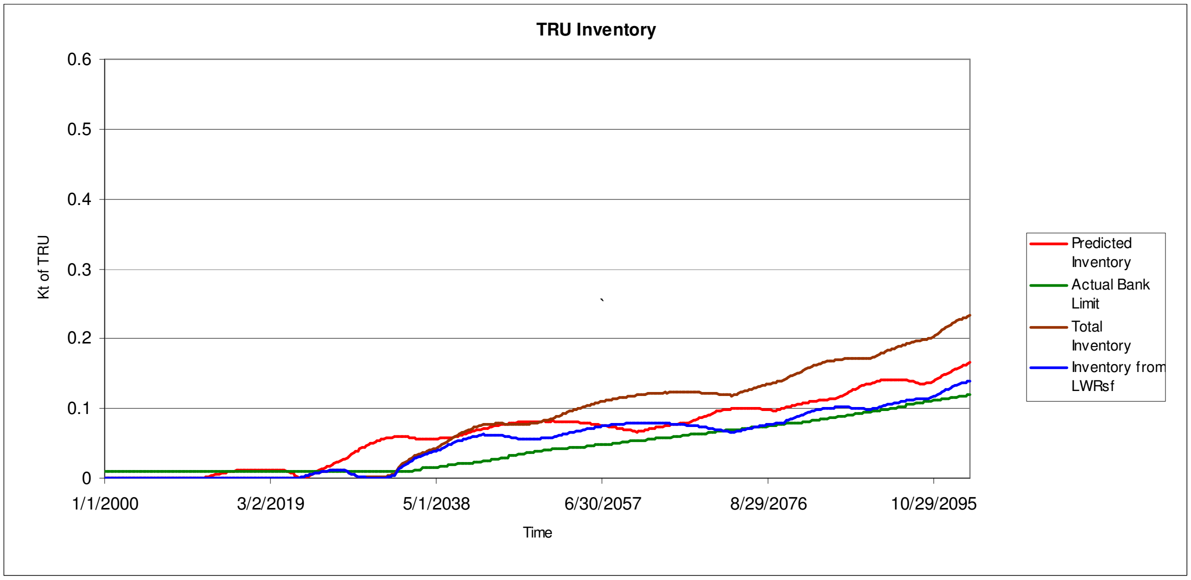

Figure 3-201: Inventory During Upset Event

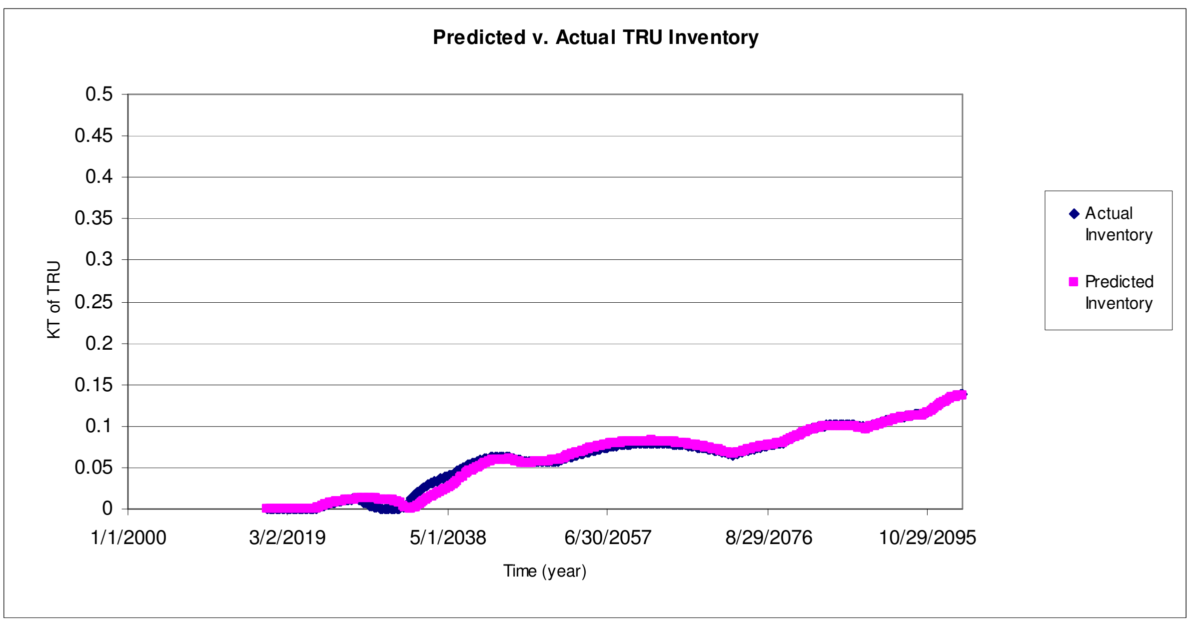

Figure 3-202: Predicted v. Actual Inventory

Scenario 2: Separation Facility Size of 0.25 Kt/yr with a 3 Year Lead Time and 10% FBR Growth

1 Separation Facility Offline between 2025 and 2029

In this scenario one separations facility goes offline starting in 2025 and comes back online in the year 2030, for a total of 5 years offline. In this case the separations facility size was decreased to 0.25 Kt/yr and as a result two separations facilities started up in the beginning. This allowed the simulation to sill have separations capacity while one facility is offline (Figure 3-203).

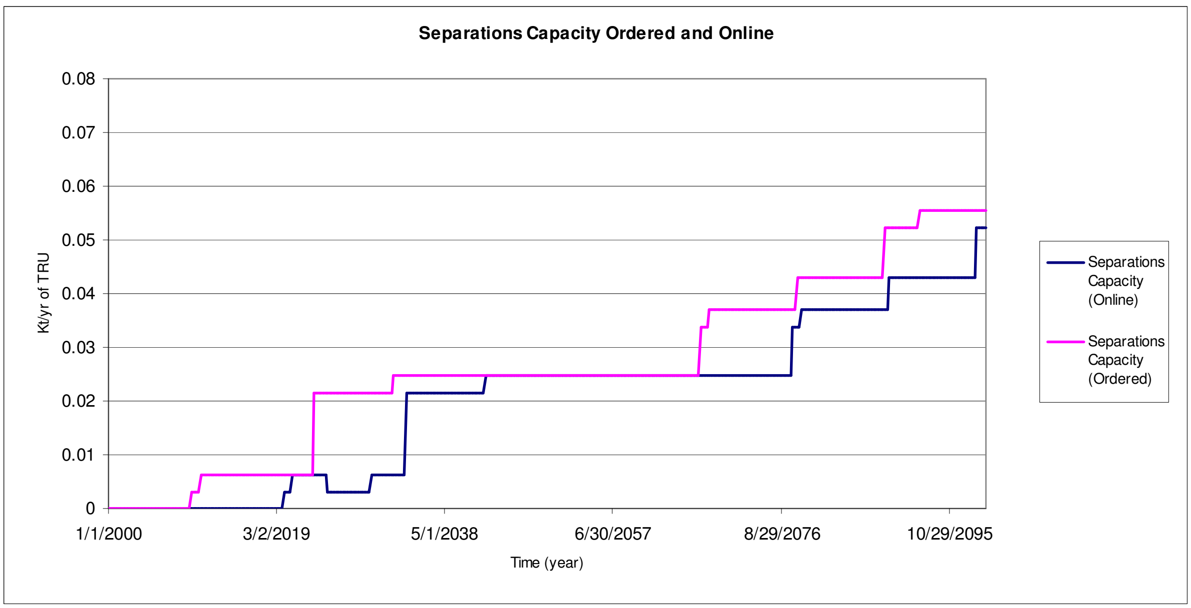

Figure 3-203: Separations Capacity During Upset Event

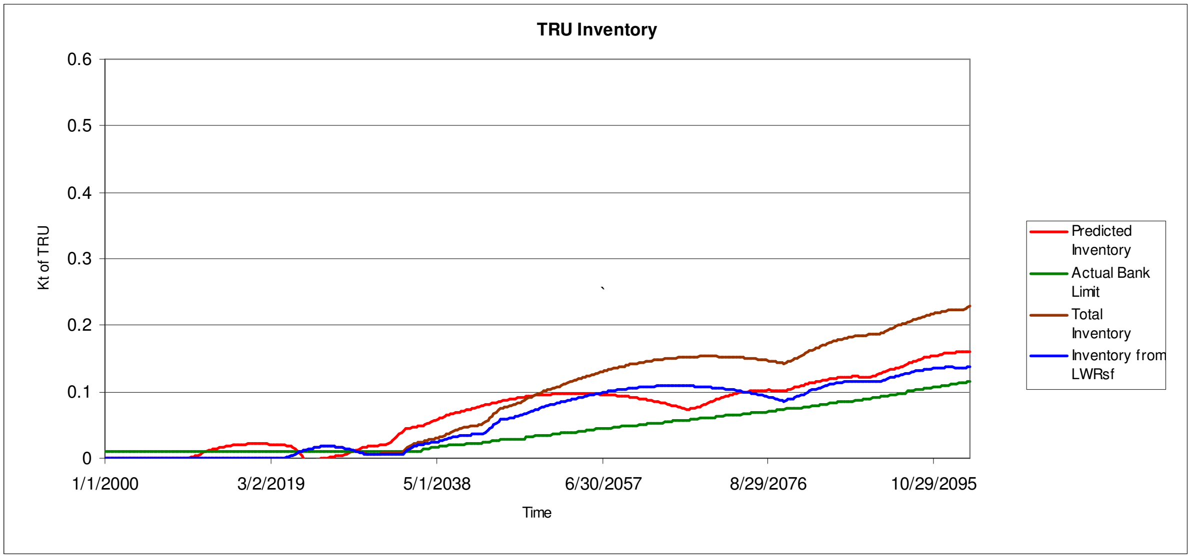

Figure 3-204: Inventory During Upset Event

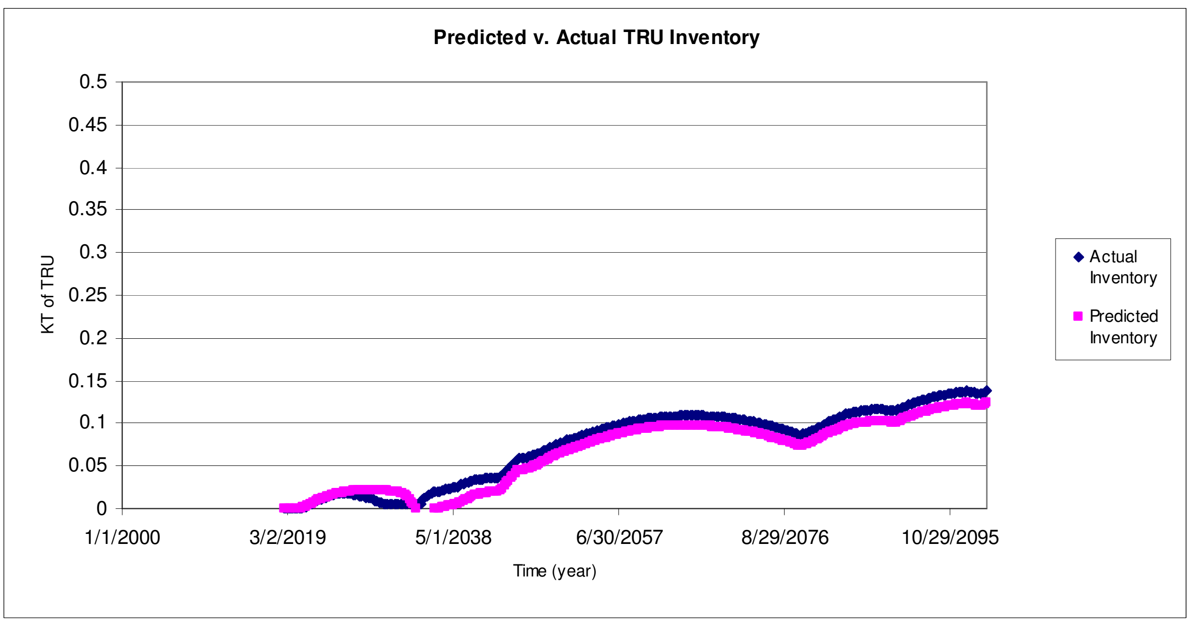

Figure 3-205: Predicted v. Actual Inventory During Upset Event

Scenario 3: Separation Facility Size of 0.5 Kt/yr with a 3 year Lead Time and 10% FBR Growth

1 Separation Facility Offline between 2025 and 2029

In this scenario one separations facility goes offline starting in 2025 and comes back online in the year 2030, for a total of 5 years offline. This is the same scenario as the previous one, except the separation facility size was increased to 0.5 kt/yr. The increase in the facility size caused the simulation to only build one facility. The predicted and actual inventory shows a greater mismatch than the first scenario because there is a longer lead time and therefore higher expected inventory.

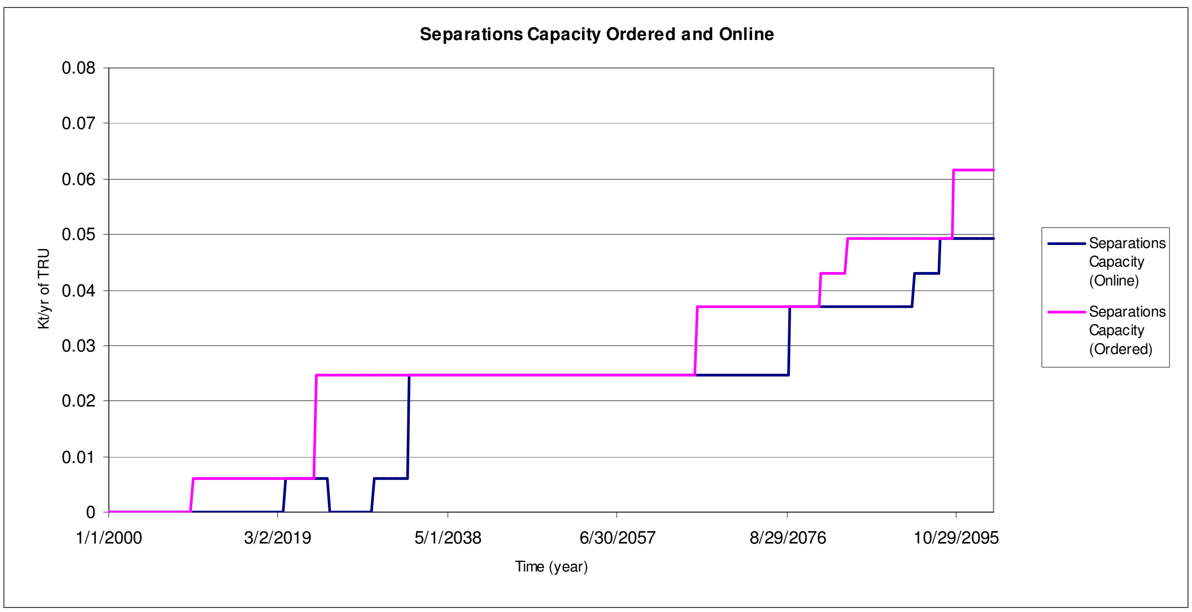

Figure 3-206: Separations Capacity During Upset Event

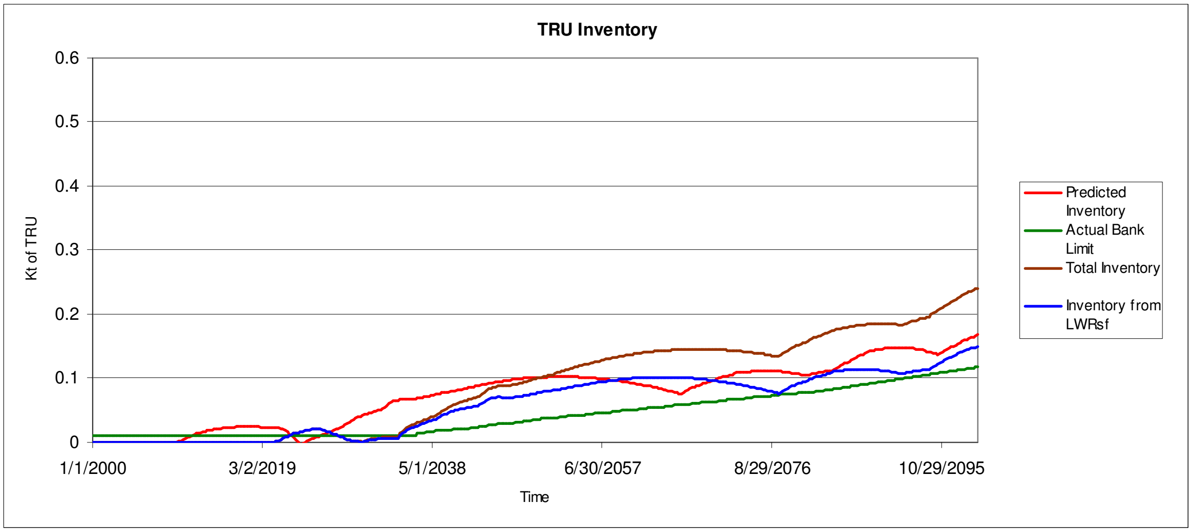

Figure 3-207: Inventory During Upset Event

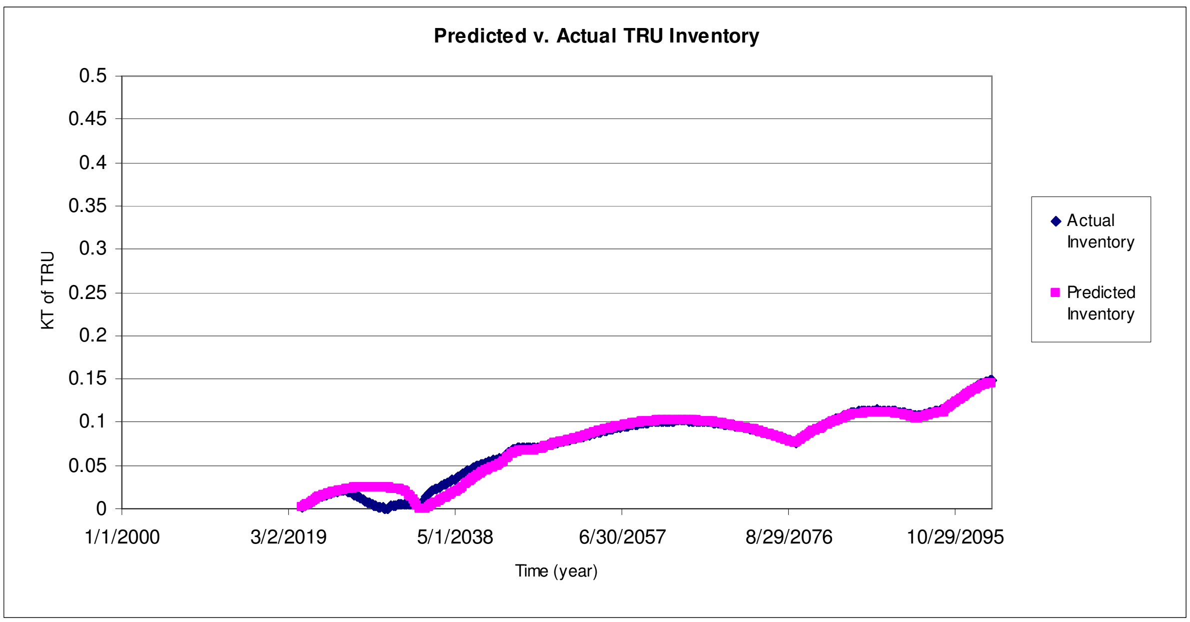

Figure 3-208: Predicted v. Actual Inventory During Upset Event

<u>Scenario 4: Separation Facility Size of 0.5 Kt/yr with a 5 year Lead Time and 10% FBR Growth</u>

<u>1 Separation Facility Offline between 2023 and 2027</u>

In this scenario one separations facility goes offline starting in 2023 and comes back online in the year 2028, for a total of 5 years offline. The lead time was increased from 3 to 5 years while the separation facility size was held at 0.5 kt/yr. Increasing the lead time actually made the upset scenario worse because the system was expecting a larger inventory at the beginning than what actually happened. This can be seen by analyzing the predicted versus actual inventory in Figure 3-212.

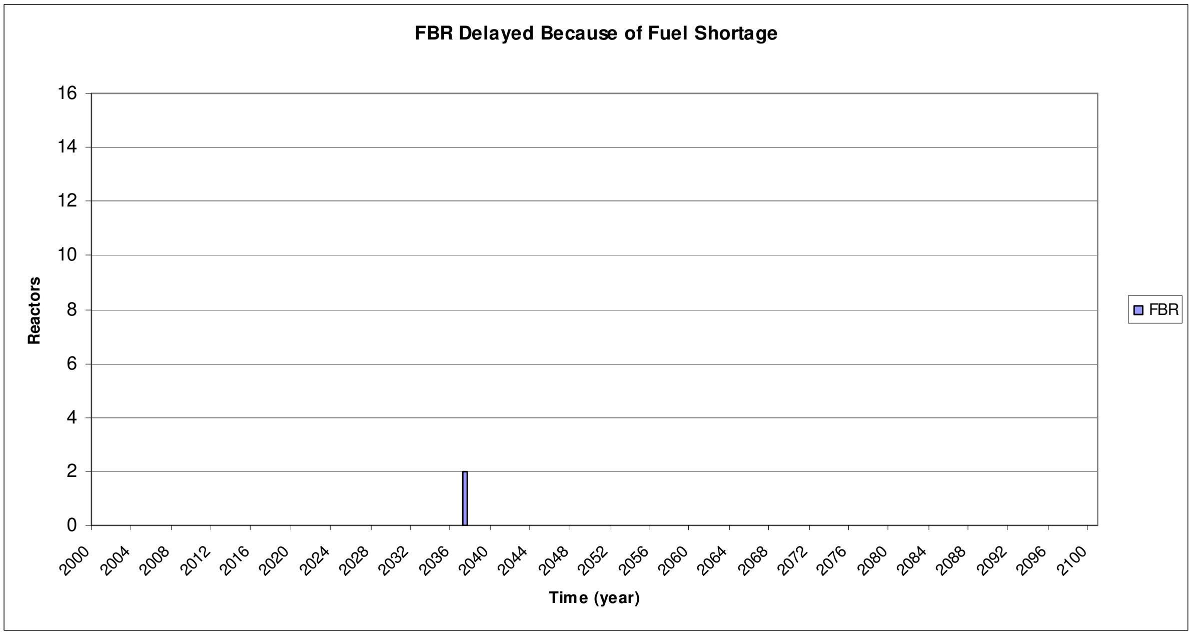

Figure 3-209: FBRs Waiting to Startup

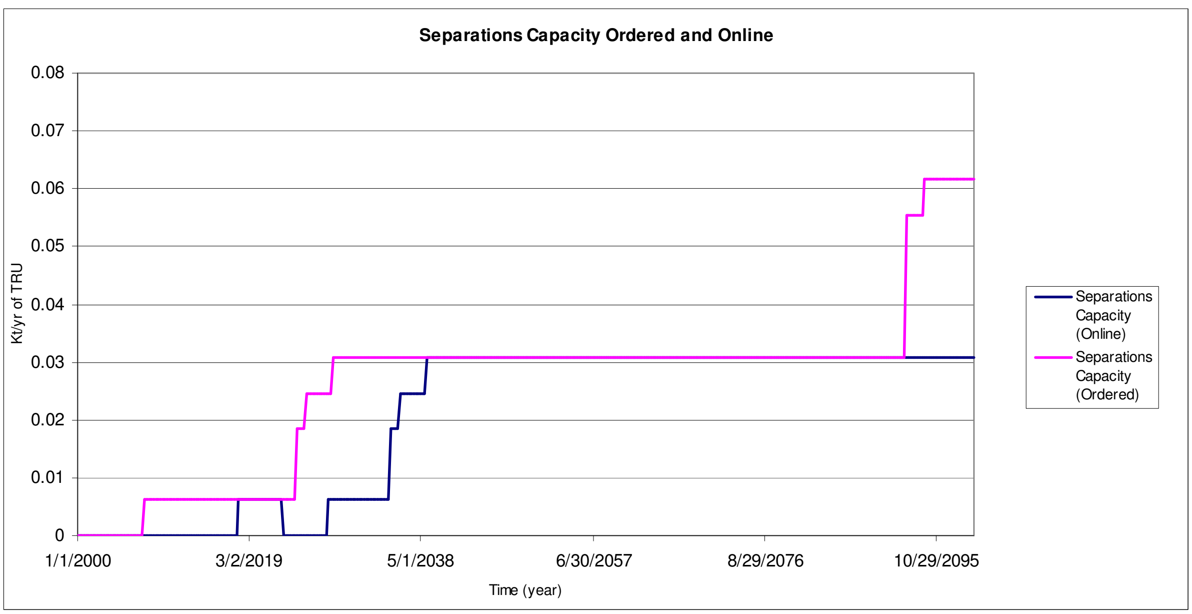

Figure 3-210: Separations Capacity During Upset Event

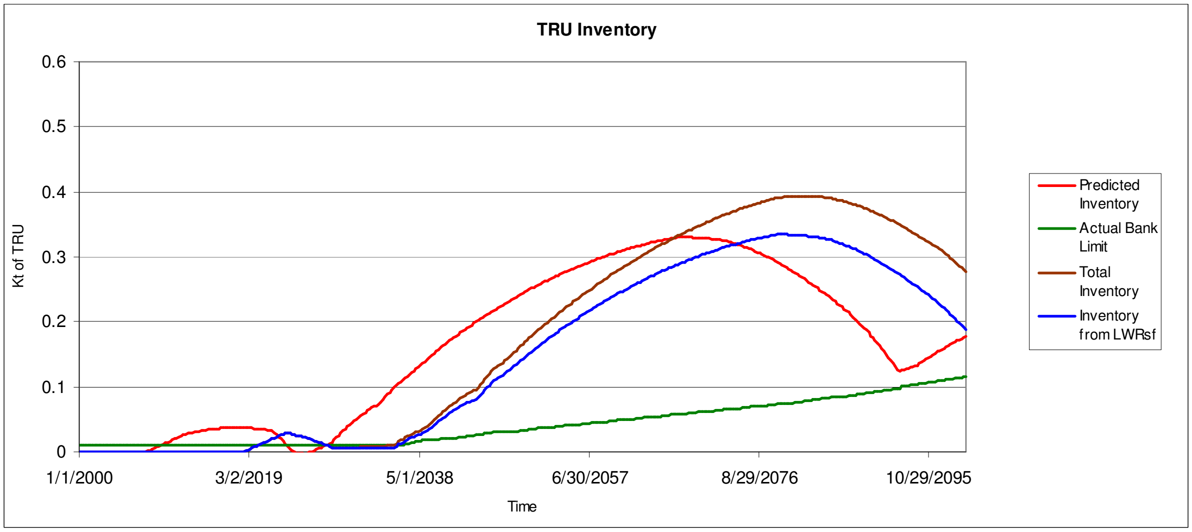

Figure 3-211: Inventory During Upset Event

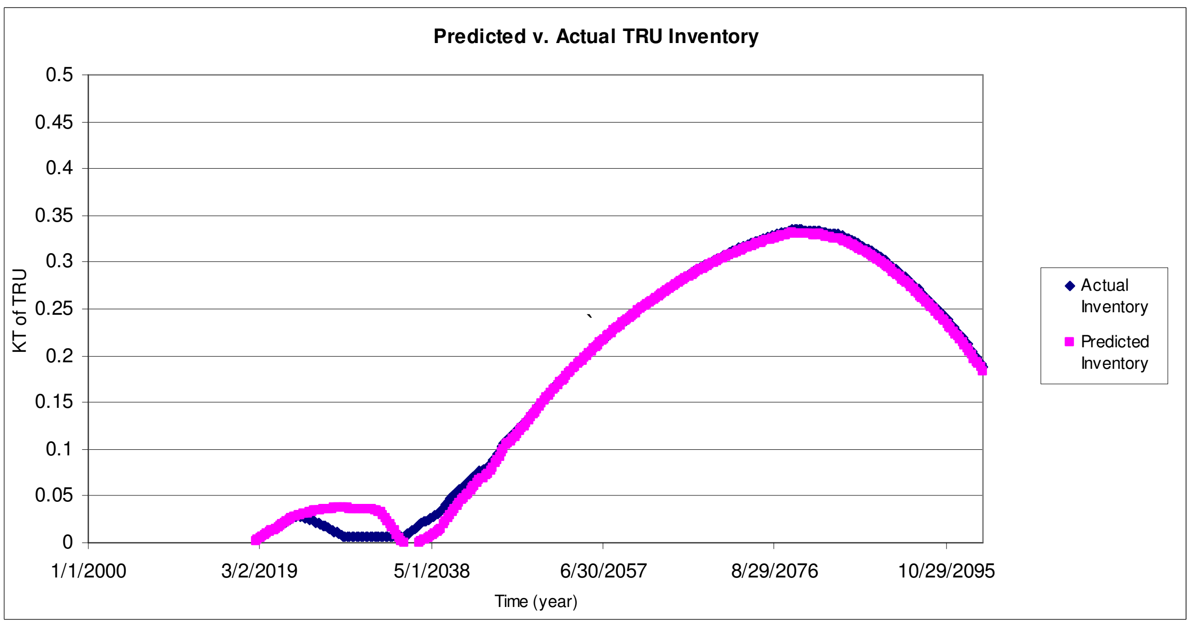

Figure 3-212: Predicted v. Actual Inventory During Upset Event

3.3.2.2 New FBR Build Held at 20% of Growth

In this section the FBR growth is held at 20% of the energy growth rate. Table 3-7 shows the scenarios that will be analyzed for this growth rate and the lost FBR GWe for each scenario. The first three are the optimum scenarios from Section 3.2, while Scenario 4 shows the affects of shifting the delay time by 5 years later and Scenario 5 shows the affects on increasing the lead time. The graphs presented in Figure 3-213 - Figure 3-216, Figure 3-217 - Figure 3-219, Figure 3-220 - Figure 3-222, Figure 3-223 - Figure 3-225, and Figure 3-226 - Figure 3-228 are the output results for Scenarios 1 -5 in Table 3-7, respectively.

Table 3-7: Scenarios for Taking 1 Separation Facility Offline with 20% FBR Growth

Scenario	Separation Facility Size	Lead Time	Years Offline	Lost FBR GWe Years
1	1 kt/yr	1 yr	2027 – 2031	1.44GWe-yr
2	0.5 kt/yr	4 yr	2024 – 2028	0GWe-yr
3	0.25 kt/yr	5 yr	2023 – 2027	0GWe-yr
4	0.25 kt/yr	5 yr	2028 – 2032	0GWe-yr
5	0.5 kt/yr	5 yr	2023 - 2027	0GWe-yr

<u>Scenario 1: Separation Facility Size of 1 Kt/yr with a 1 year Lead Time and 20% FBR Growth</u>

In this scenario one separations facility goes offline starting in 2027 and comes back online in the year 2032, for a total of 5 years offline. This scenario results in several FBRs waiting for startup fuel as a result of a much lower initial inventory than expected.

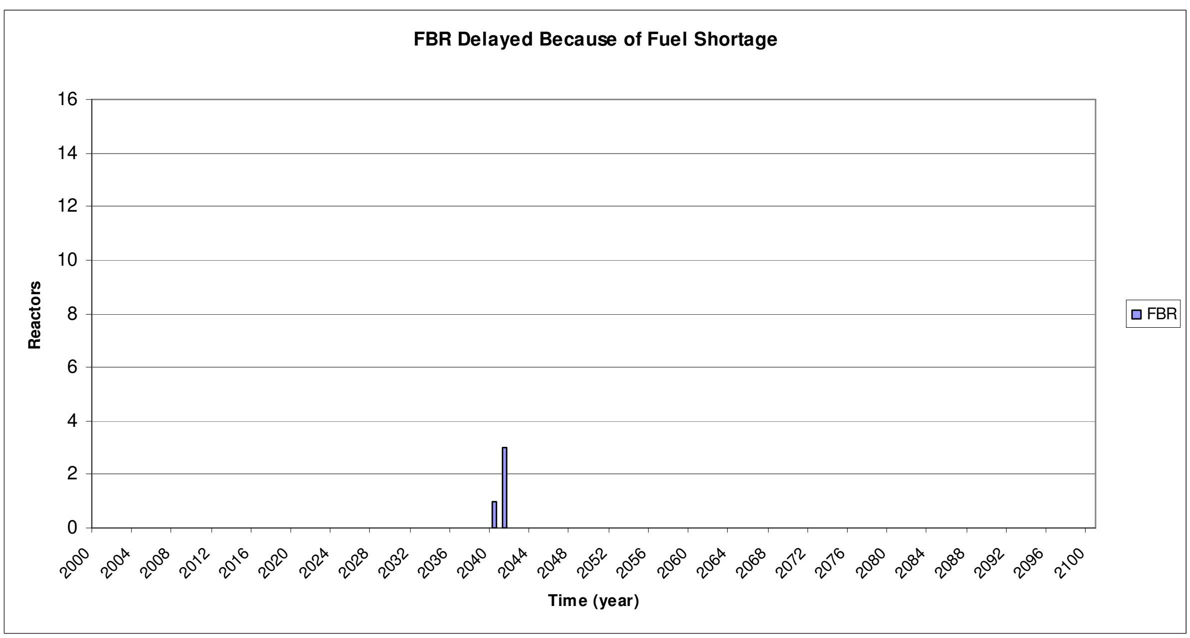

Figure 3-213: FBRs Waiting to Startup

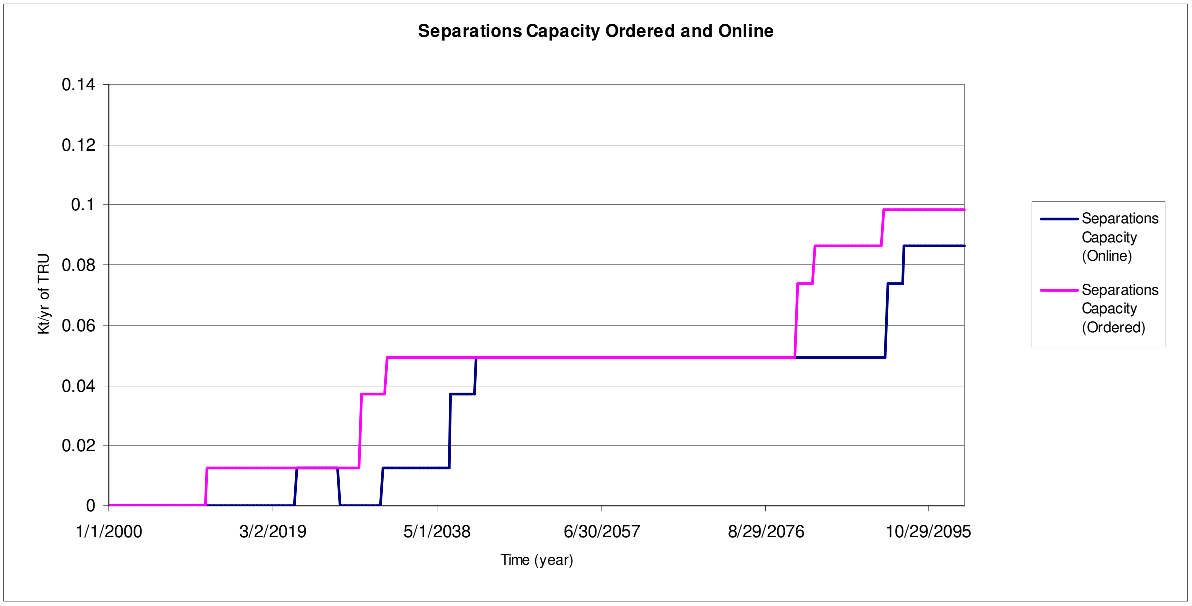

Figure 3-214: Separations Capacity During Upset Event

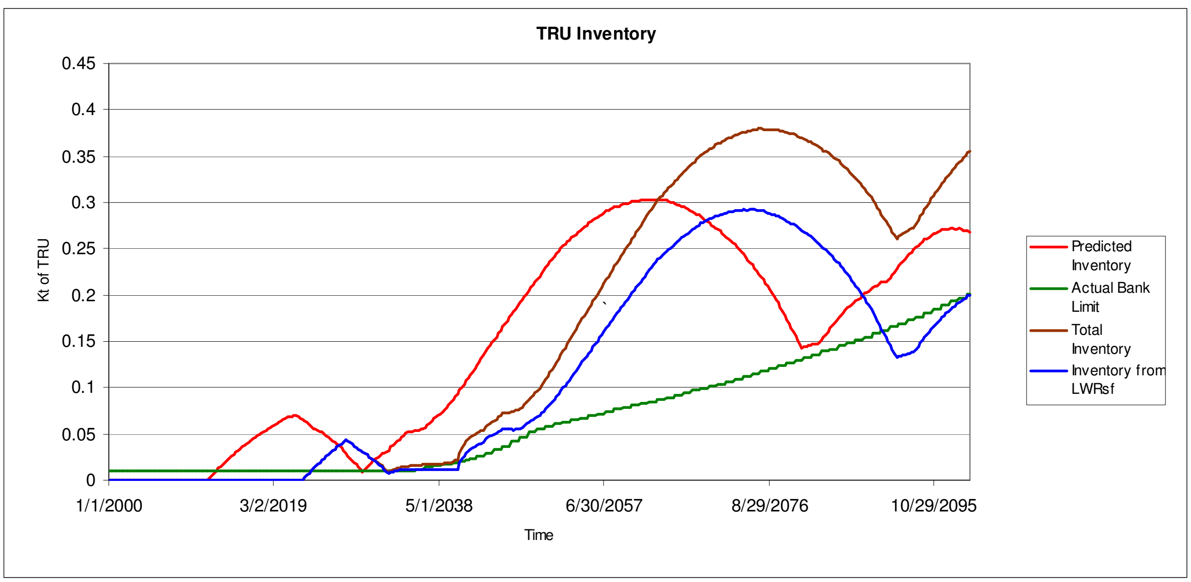

Figure 3-215: Inventory During Upset Event

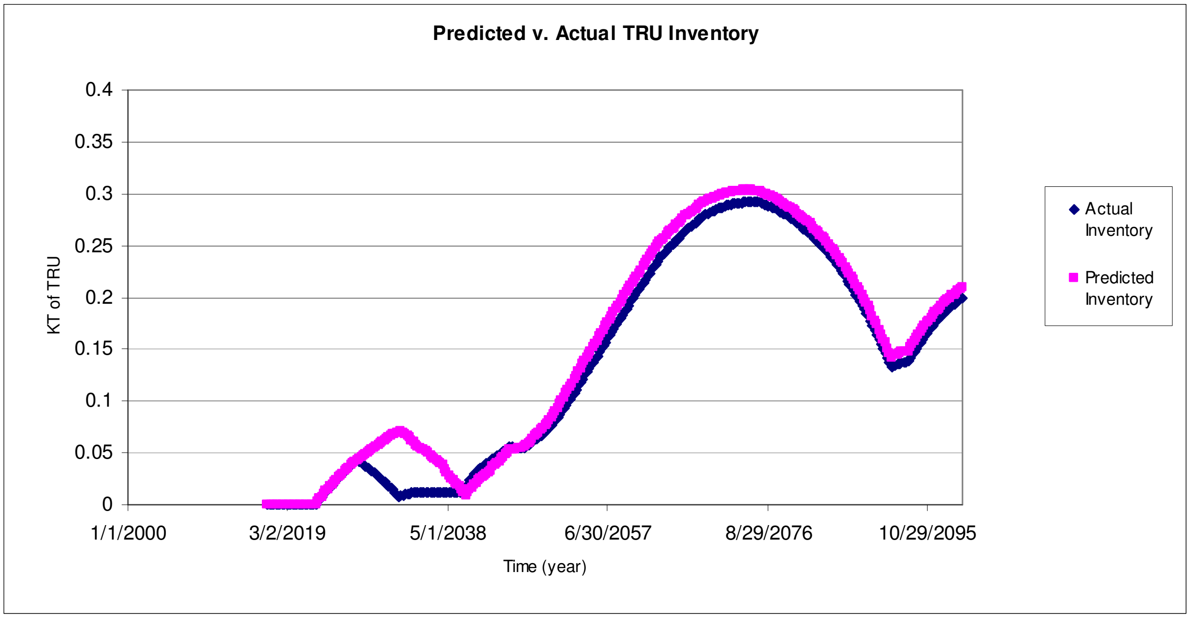

Figure 3-216: Predicted v. Actual Inventory During Upset Event

Scenario 2: Separation Facility Size of 0.5 Kt/yr with a 4 year Lead Time and 20% FBR Growth

In this scenario one separations facility goes offline starting in 2024 and comes back online in the year 2029, for a total of 5 years offline. The decreased separations facility capacity helps to decrease the number of FBRs that are waiting for startup fuel because the expected initial inventory is not as large as the initial inventory from Scenario 1 (Figure 3-216 and Figure 3-219).

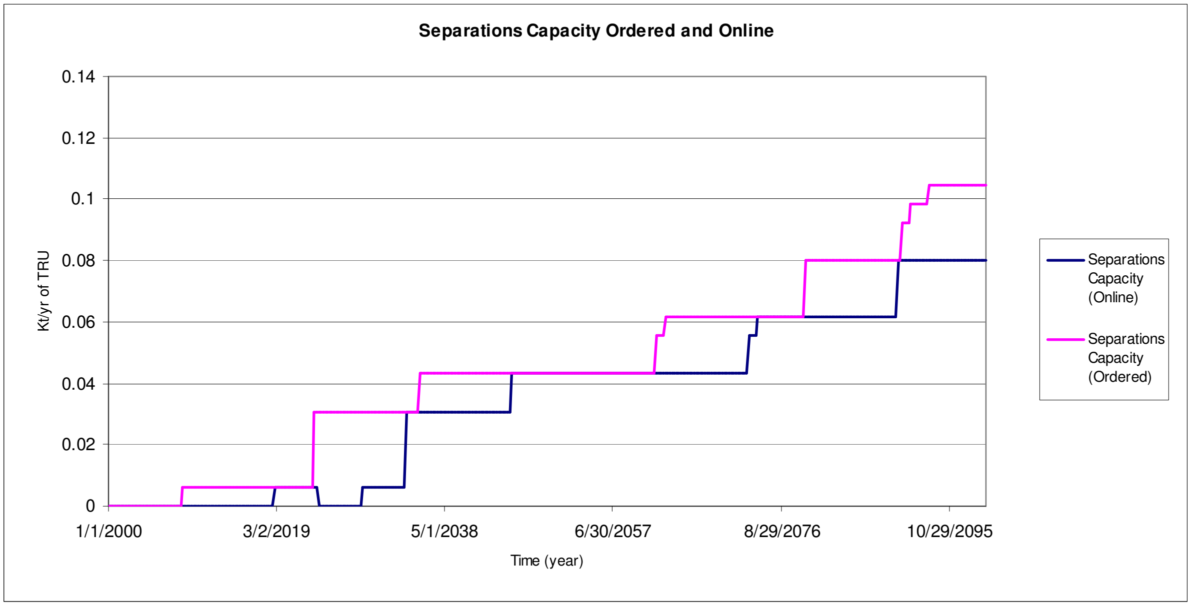

Figure 3-217: Separations Capacity During Upset Event

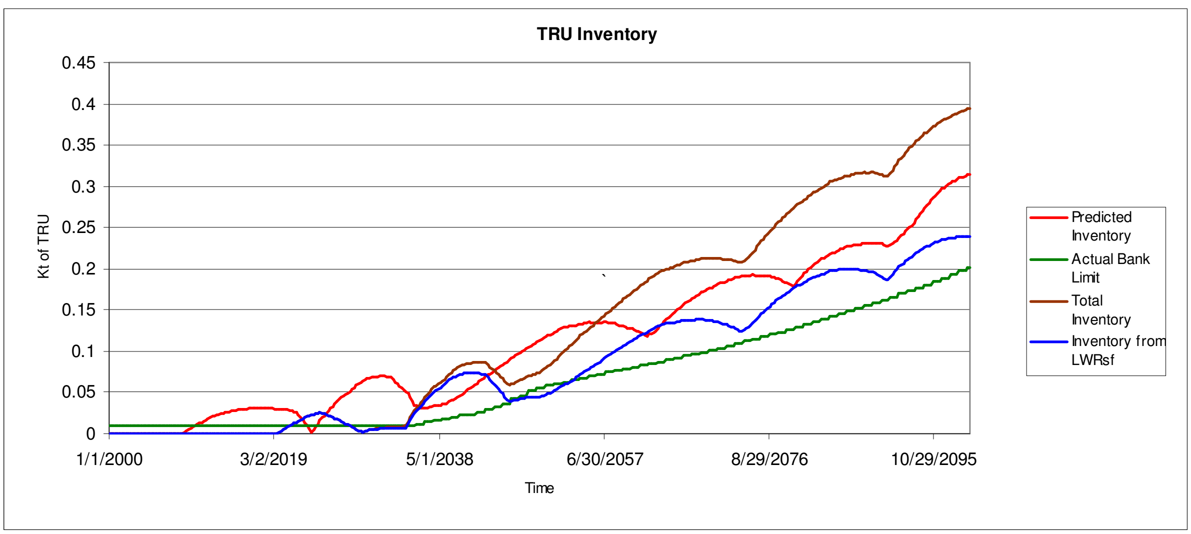

Figure 3-218: Inventory with Upset Event

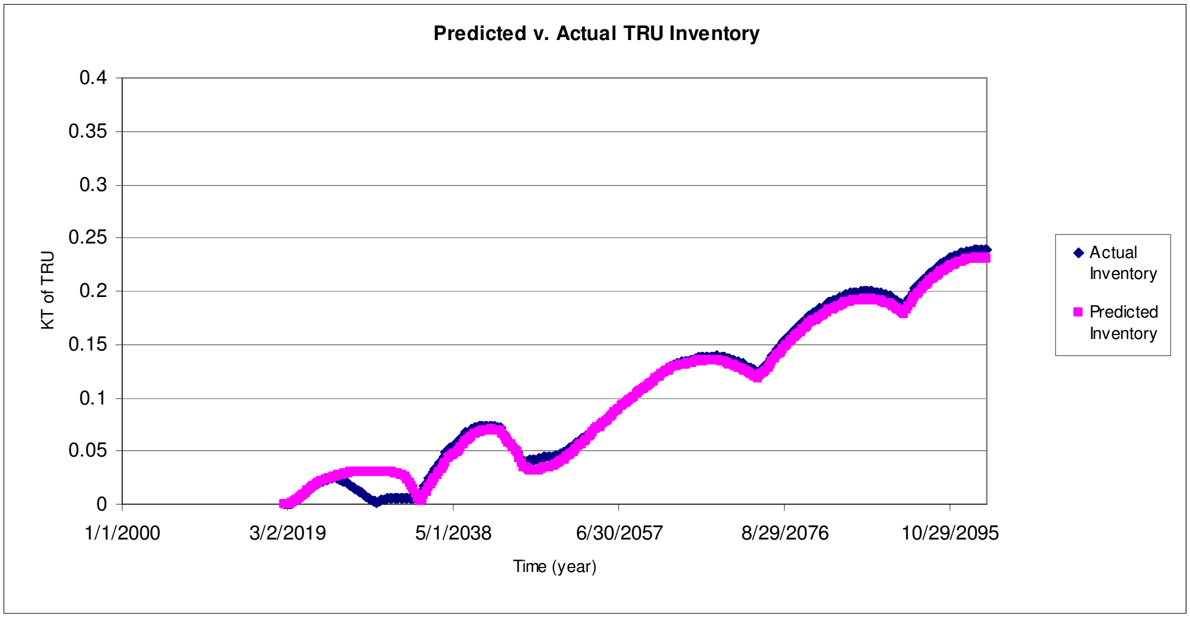

Figure 3-219: Predicted v. Actual Inventory During Upset Event

Scenario 3: Separation Facility Size of 0.25 Kt/yr with a 5 year Lead Time and 20% FBR Growth

In this scenario one separations facility goes offline starting in 2023 and comes back online in the year 2028, for a total of 5 years offline. In this scenario no FBRs were waiting for startup fuel. This is a direct result of the separation facility size, because with the small separation facility size 2 facilities are built at the beginning of the simulation. This allows one facility to operate while the other facility is shutdown (Figure 3-222).

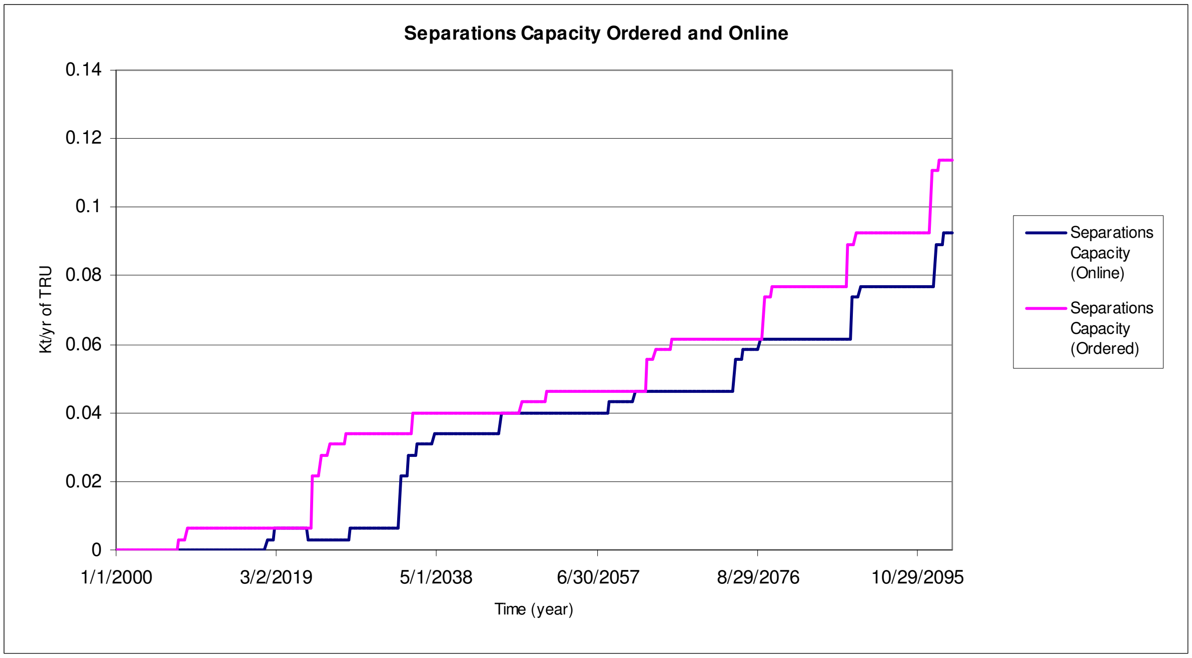

Figure 3-220: Separations Capacity During Upset Event

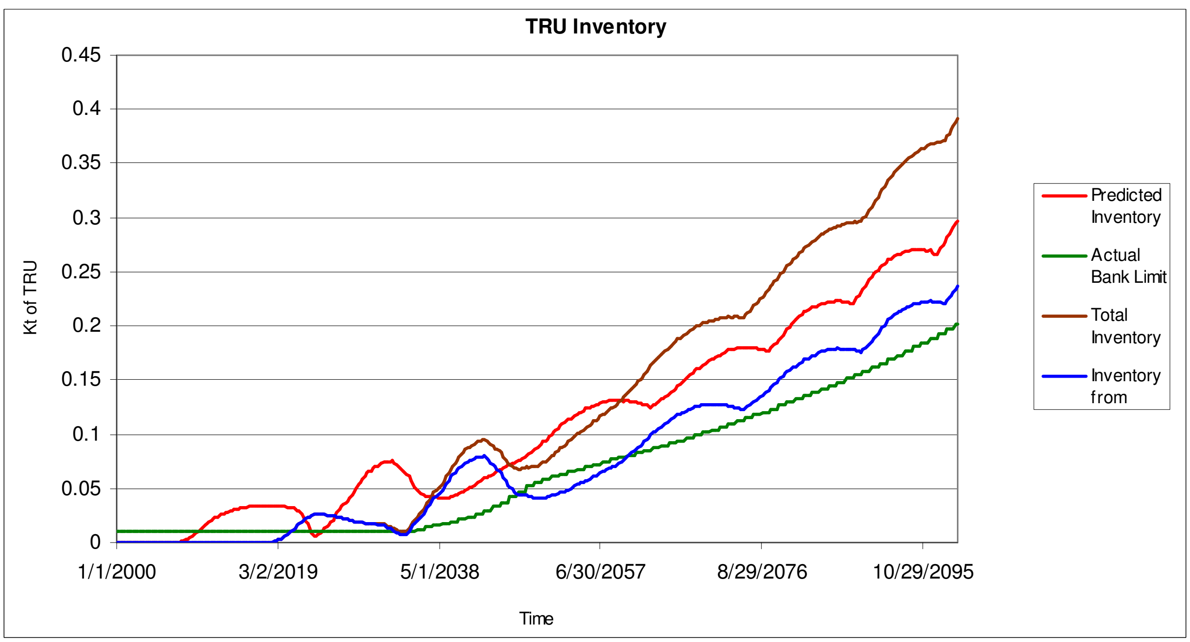

Figure 3-221: Inventory During Upset Event

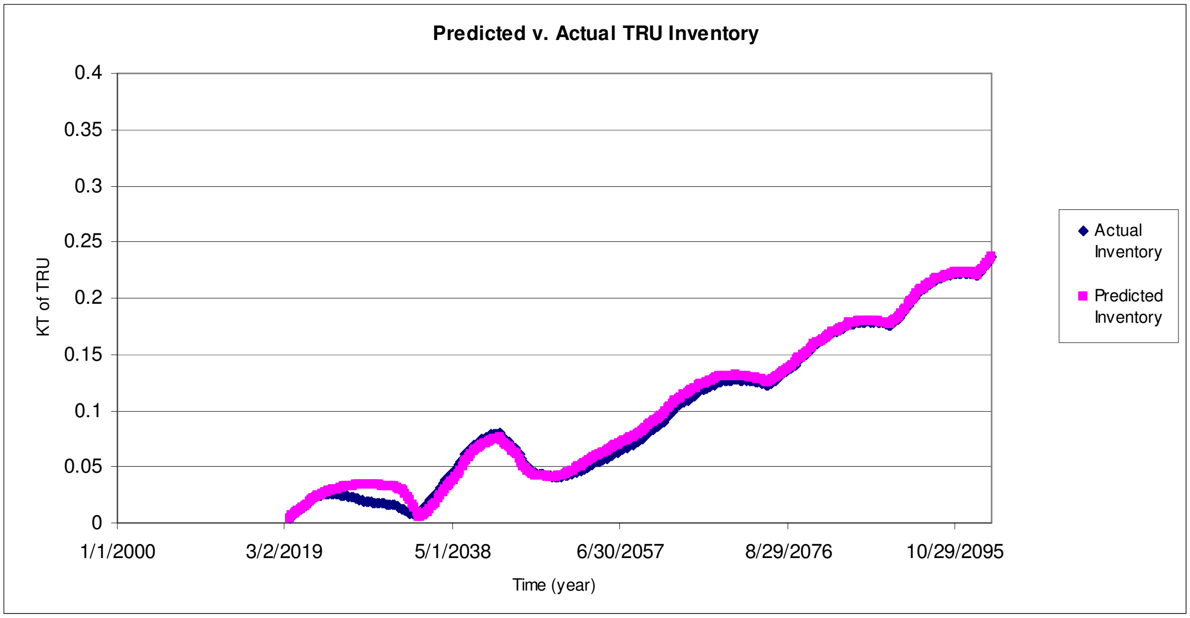

Figure 3-222: Predicted v. Actual Inventory with Upset Event

Scenario 4: Separation Facility Size of 0.25 Kt/yr with a 5 year Lead Time and 20% FBR Growth

In this scenario one separations facility goes offline starting in 2028 and comes back online in the year 2032, for a total of 5 years offline. This is a 5 year shift in the upset event from Scenario 3. The affects of this change are minimum because an initial inventory is able to accumulate (Figure 3-225) and the second separation facility is able to continue operation (Figure 3-223).

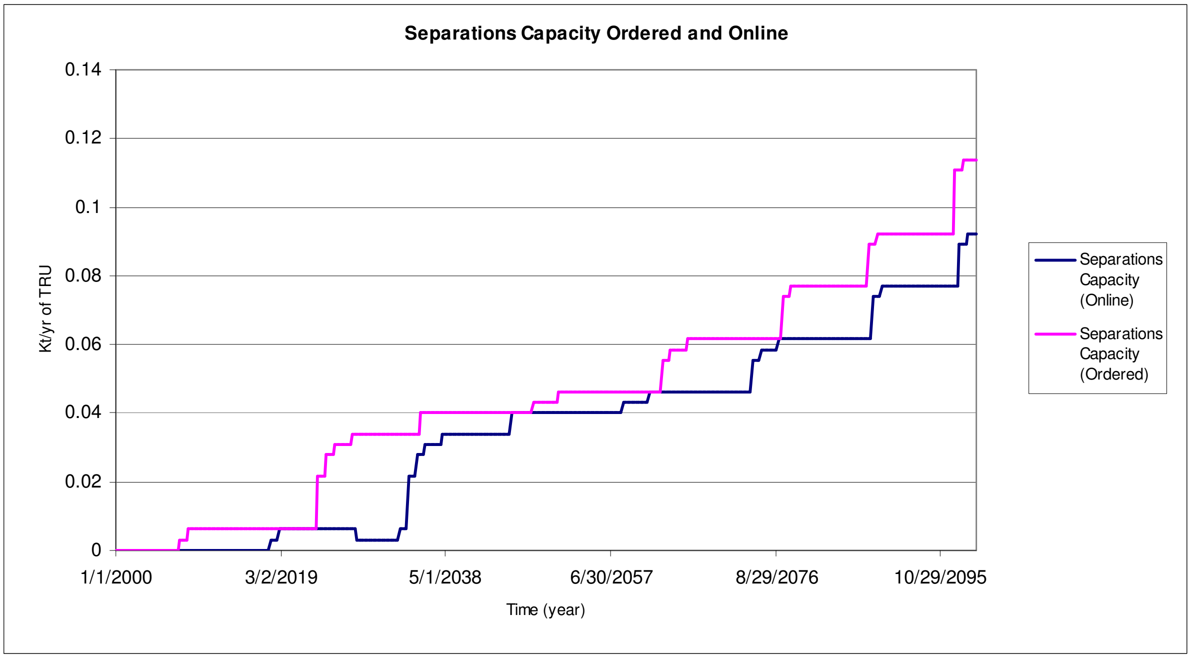

Figure 3-223: Separations Capacity During Upset Event

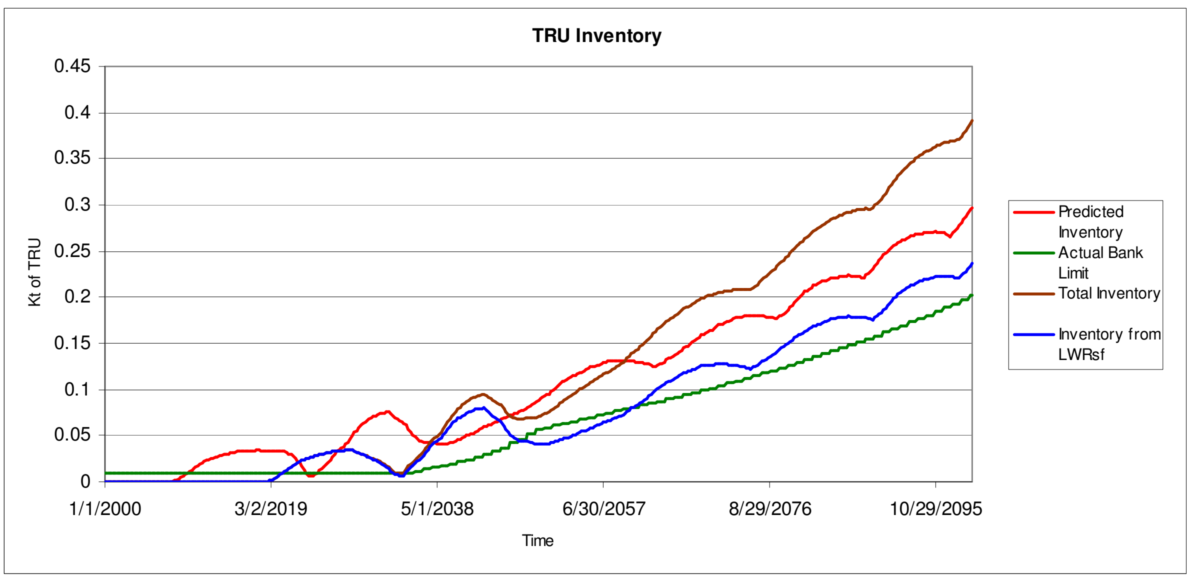

Figure 3-224: Inventory During Upset Event

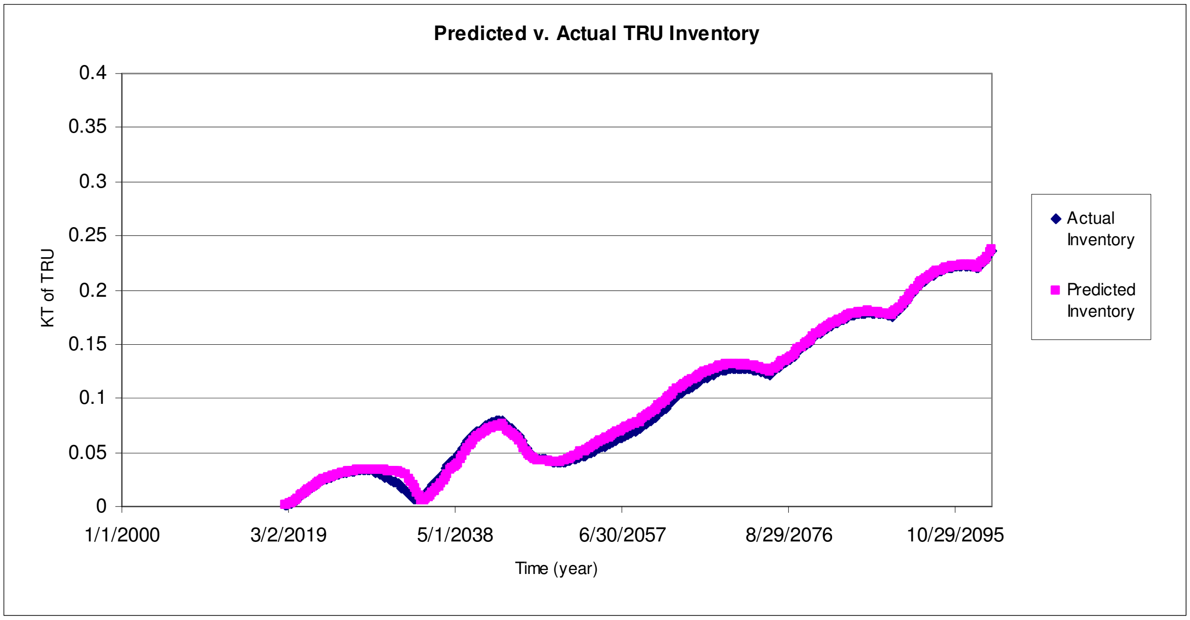

Figure 3-225: Predicted v. Actual Inventory During Upset Event

Scenario 5: Separation Facility Size of 0. 5 Kt/yr with a 5 year Lead Time and 20% FBR Growth

In this scenario one separations facility goes offline starting in 2023 and comes back online in the year 2028, for a total of 5 years offline. This is an increase in the lead time by 1 year from Scenario 3.

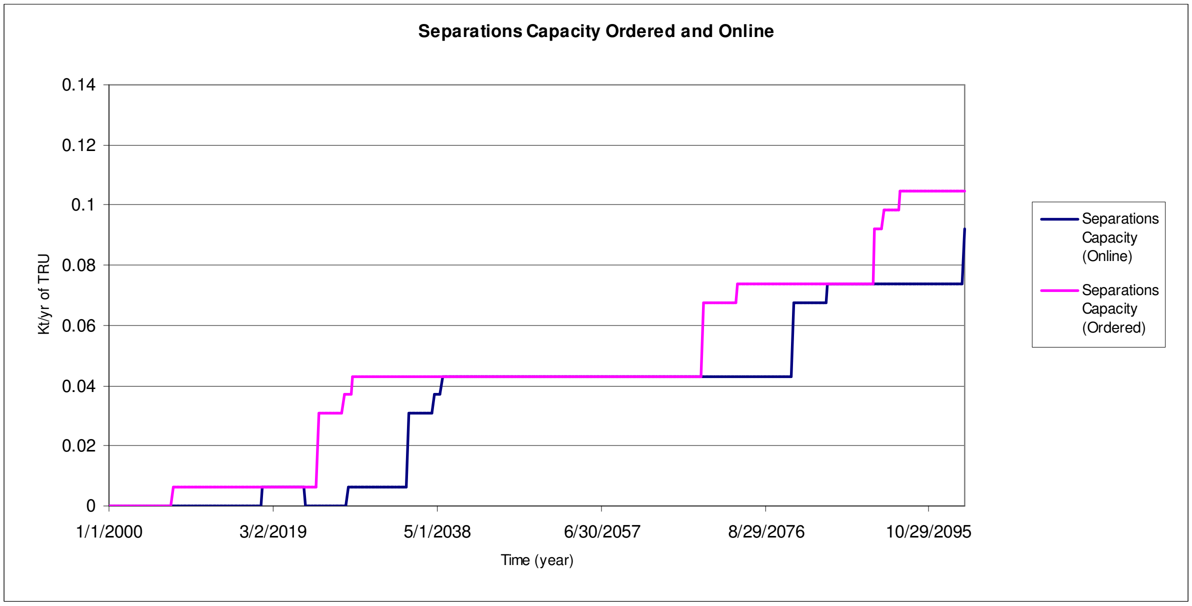

Figure 3-226: Separations Capacity During Upset Event

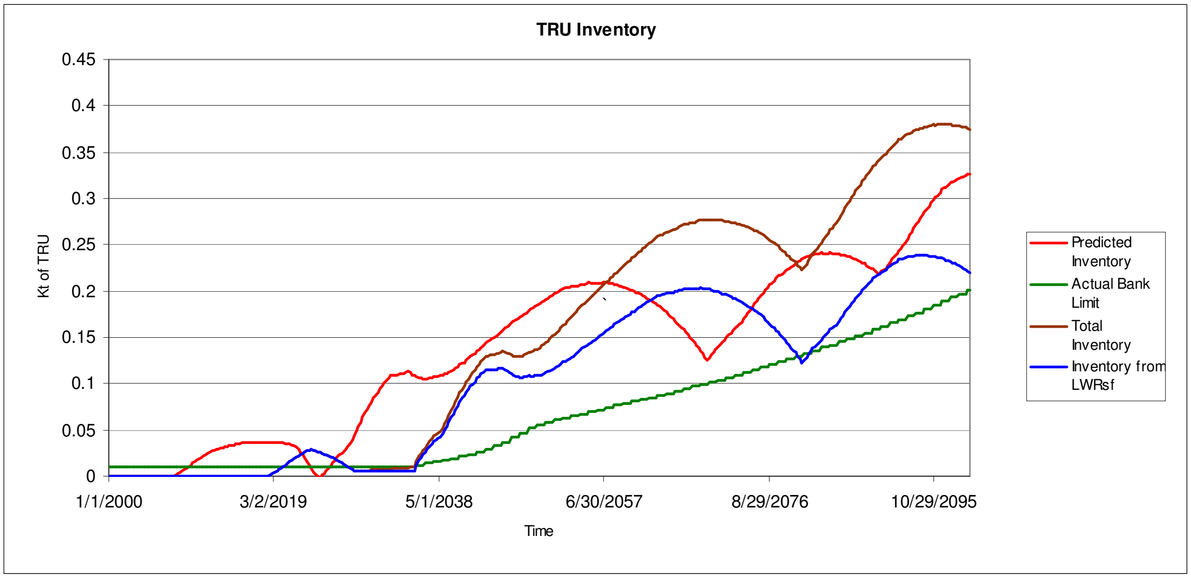

Figure 3-227: Inventory During Upset Event

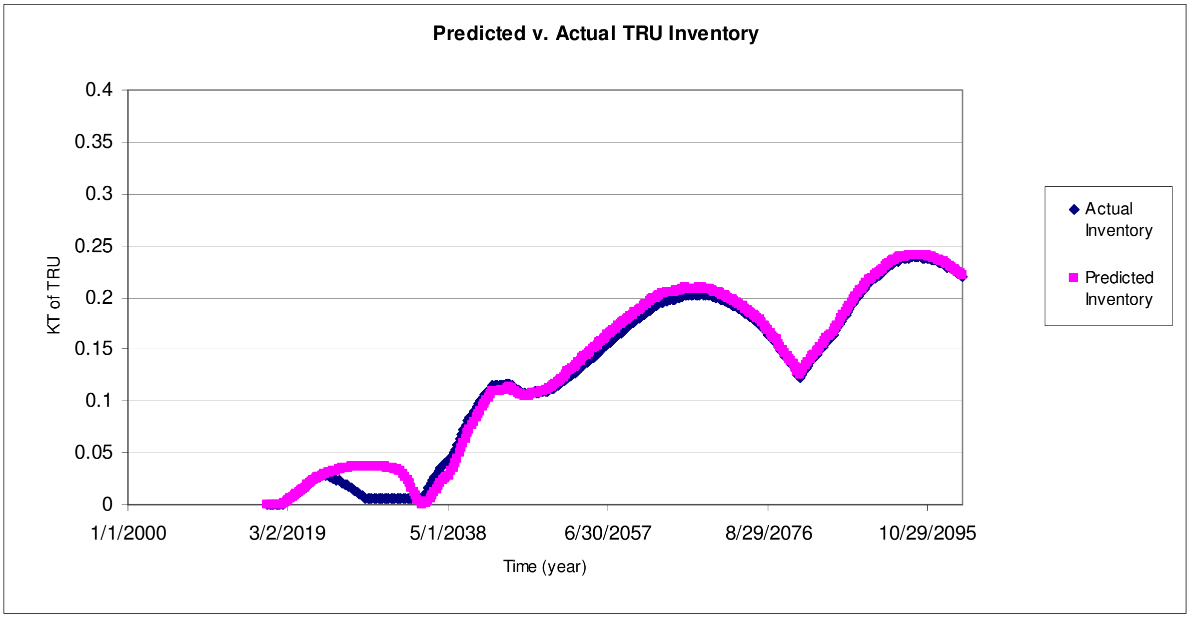

Figure 3-228: Predicted v. Actual Inventory During Upset Event

3.3.2.3 New FBR Ramped up to 100% of Growth Rate or Max Value

In the following scenarios the FBRs will be ramped up and built at the maximum rate possible. All scenarios will have one separation facility going offline after 5 years of operation and remain offline for 5 years. The first two scenarios are taken from the optimum scenarios in Section 3.2, while the last scenario is an analysis on the decrease in lead time. Table 3-8 shows a summary of the scenarios that are run for this case and the lost FBR GWe due to FBRs not being able to start up on time. The graphs presented in Figure 3-229 - Figure 3-231, Figure 3-232 - Figure 3-234, and Figure 3-235 - Figure 3-237 are the output results for Scenarios 1 – 3 in Table 3-8, respectively.

Table 3-8: Scenarios for Taking 1 Separation Facility Offline with 100% FBR Growth

Scenario	Separation Facility Size	Lead Time	Years Offline	Lost FBR GWe Years
1	0.5 kt/yr	7 yr	2022 – 2026	0GWe-yr
2	0.25 kt/yr	7 yr	2022 – 2026	0GWe-yr
3	0.25 kt/yr	5 yr	2024 – 2028	0GWe-yr

Scenario 1: Separation Facility Size of 0. 5 Kt/yr with a 7 year Lead Time with 100% FBR Growth

In this scenario one separations facility goes offline starting in 2022 and comes back online in the year 2027, for a total of 5 years offline. There are no FBRs left waiting for startup fuel primarily because of the large amount of separations capacity that comes online shortly after the delay (Figure 3-229).

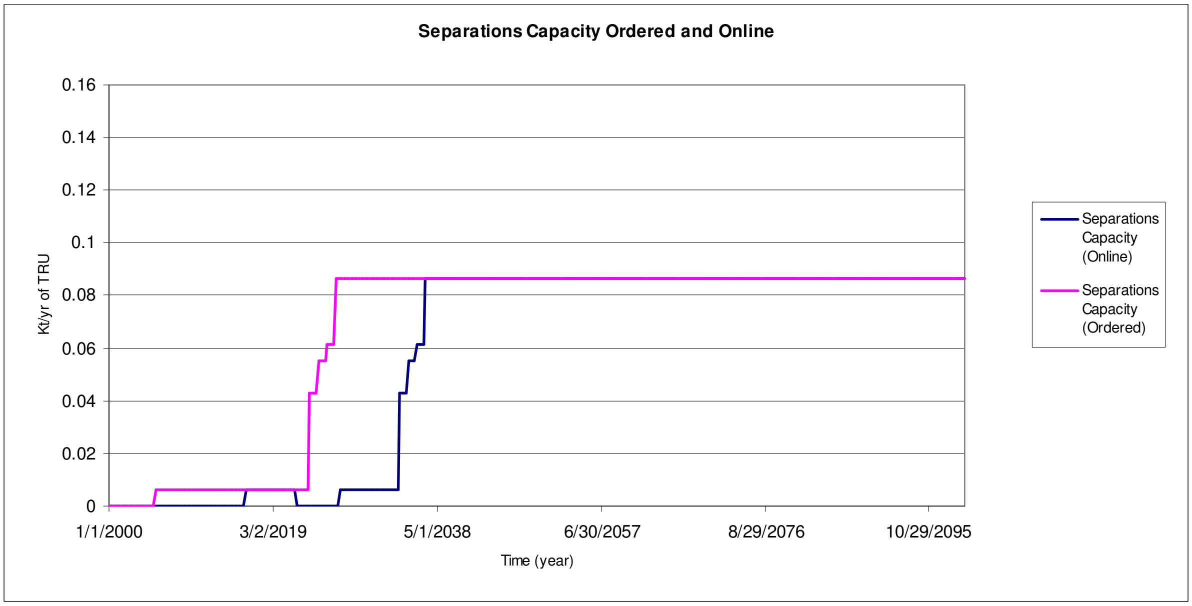

Figure 3-229: Separations Capacity with Upset Event

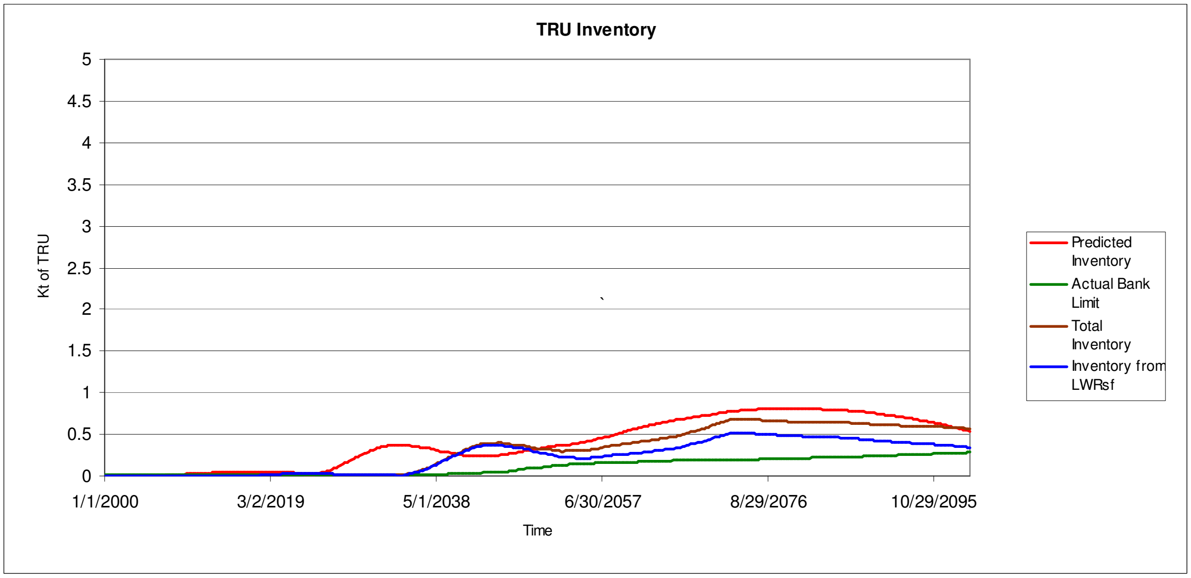

Figure 3-230: Inventory with Upset Event

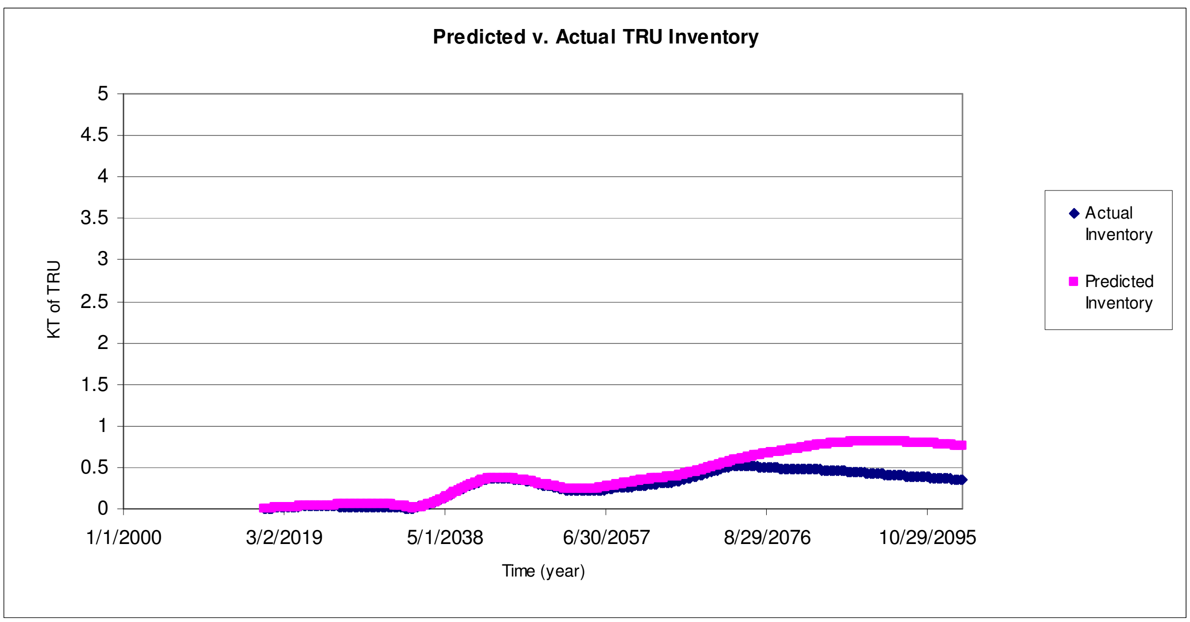

Figure 3-231: Predicted v. Actual Inventory with Upset Event

Scenario 2: Separation Facility Size of 0. 25 Kt/yr with a 7 year Lead Time and 100% FBR Growth

In this scenario one separations facility goes offline starting in 2022 and comes back online in the year 2027, for a total of 5 years offline. There are two facilities operating when one of the facilities is shutdown, therefore this allows the system to recover better.

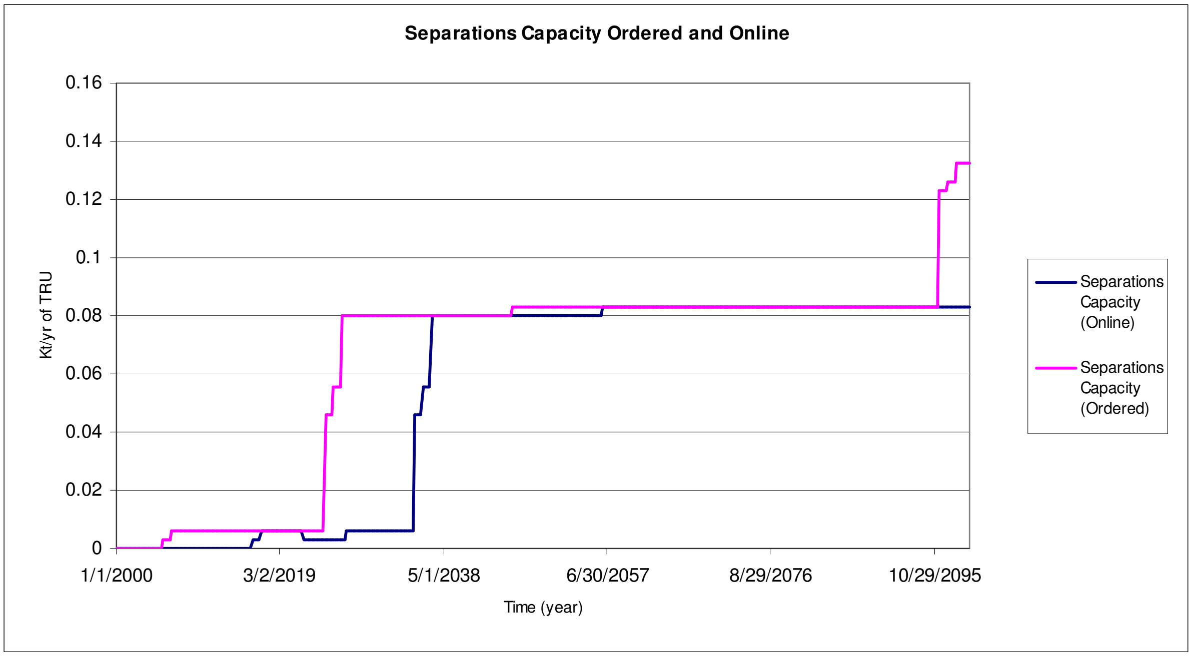

Figure 3-232: Separations Capacity with Upset Event

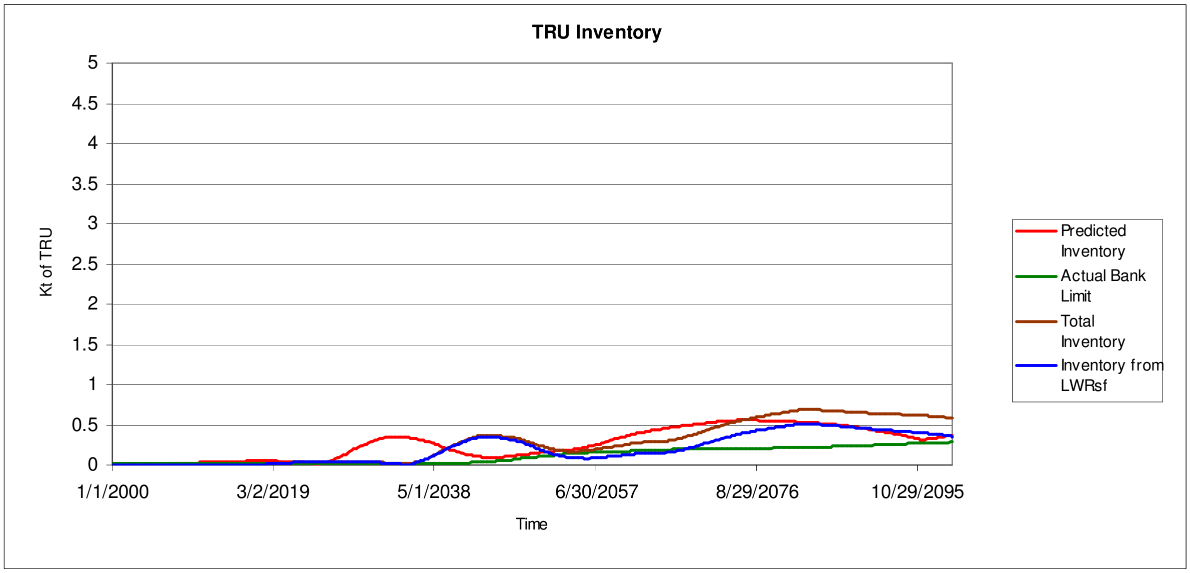

Figure 3-233: Inventory with Upset Event

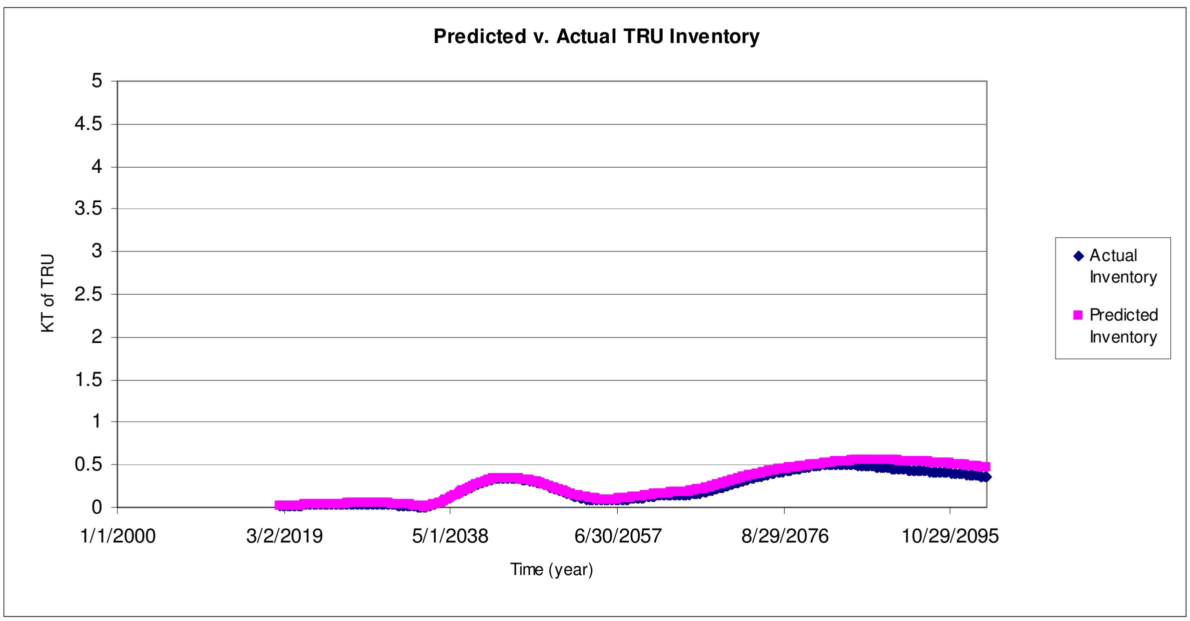

Figure 3-234: Predicted v. Actual Inventory with Upset Event

Scenario 3: Separation Facility Size of 0. 25 Kt/yr with a 5 year Lead Time an 100% FBR Growth

In this scenario one separations facility goes offline starting in 2024 and comes back online in the year 2029, for a total of 5 years offline. Decreasing the lead time by 2 years only causes the simulation to overbuild separations facilities, which can be seen by the large predicted inventory in Figure 3-235 and Figure 3-236.

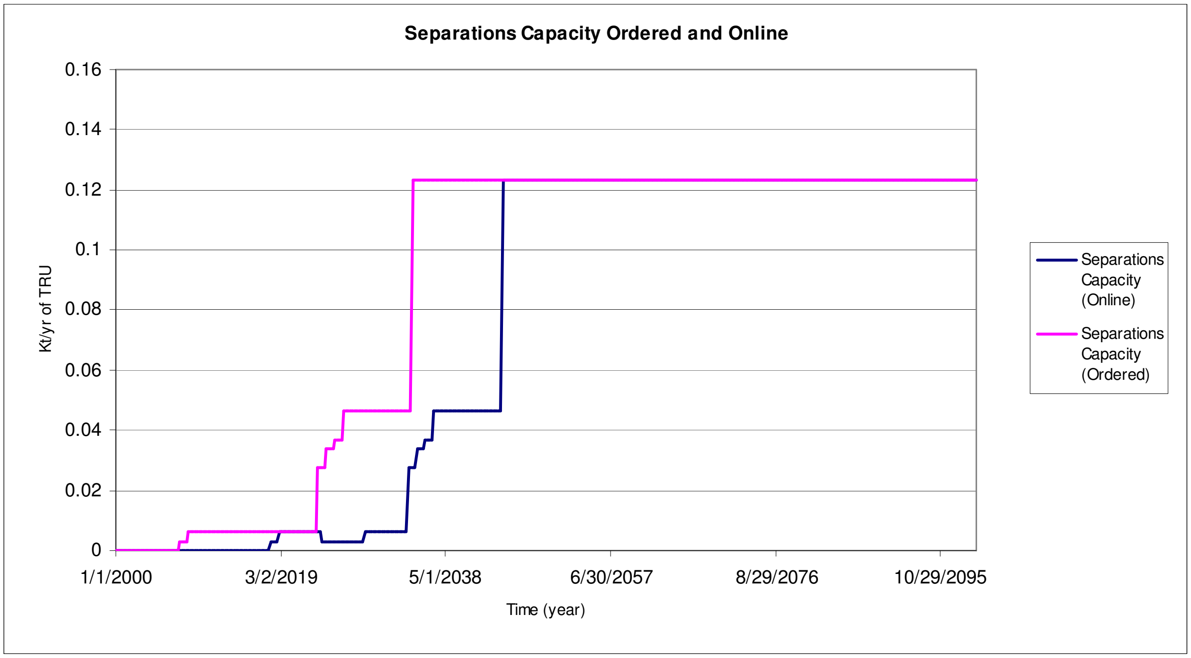

Figure 3-235: Separations Capacity with Upset Event

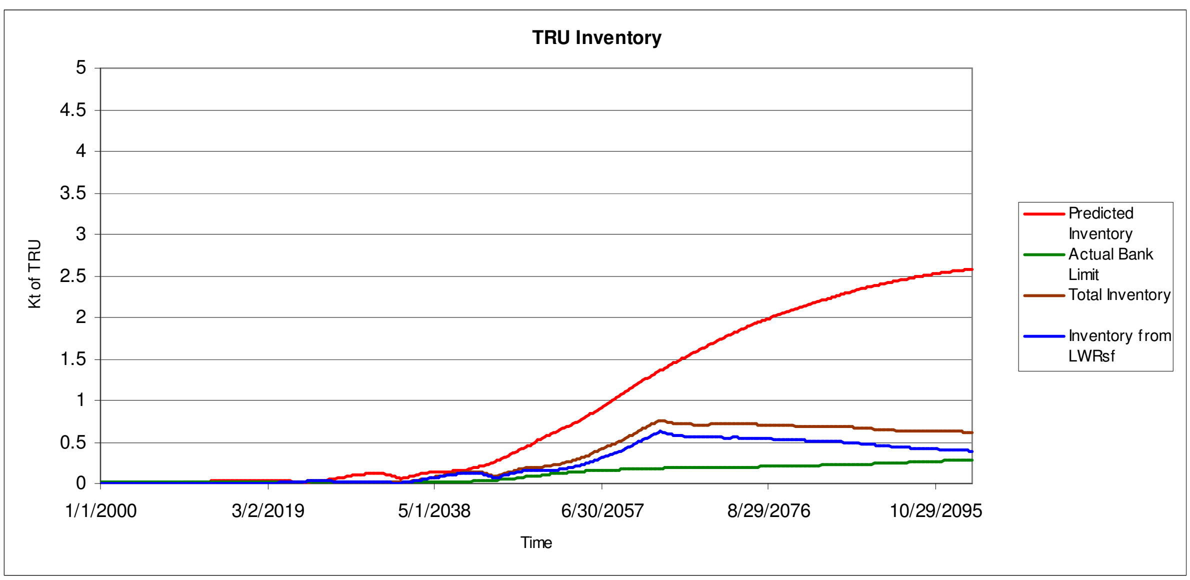

Figure 3-236: Inventory with Upset Event

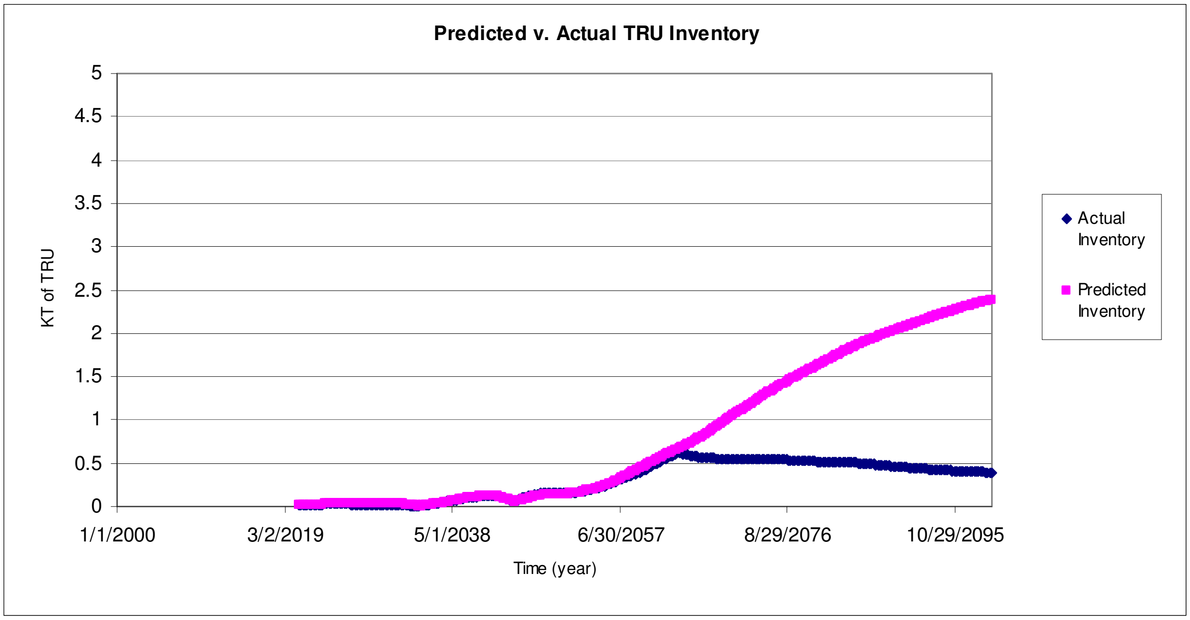

Figure 3-237: Predicted v. Actual Inventory with Upset Event

3.3.2.4 Separation Facility Shutdown for 5 Years after 40 Years of Operation

To understand how the inventory will respond to a separation facility being taken offline after a number of years of operation, the following scenario will be studied. The scenario that will be analyzed is from Case 5 in Section 3.2 where the FBR deployment is held to 20% of the electric growth rate. The separation facility size is 0.5 kt/yr with a 4 year lead time. One separation facility will be taken offline from 2058 through 2062 and the results are presented below in Figure 3-238 - Figure 3-240.

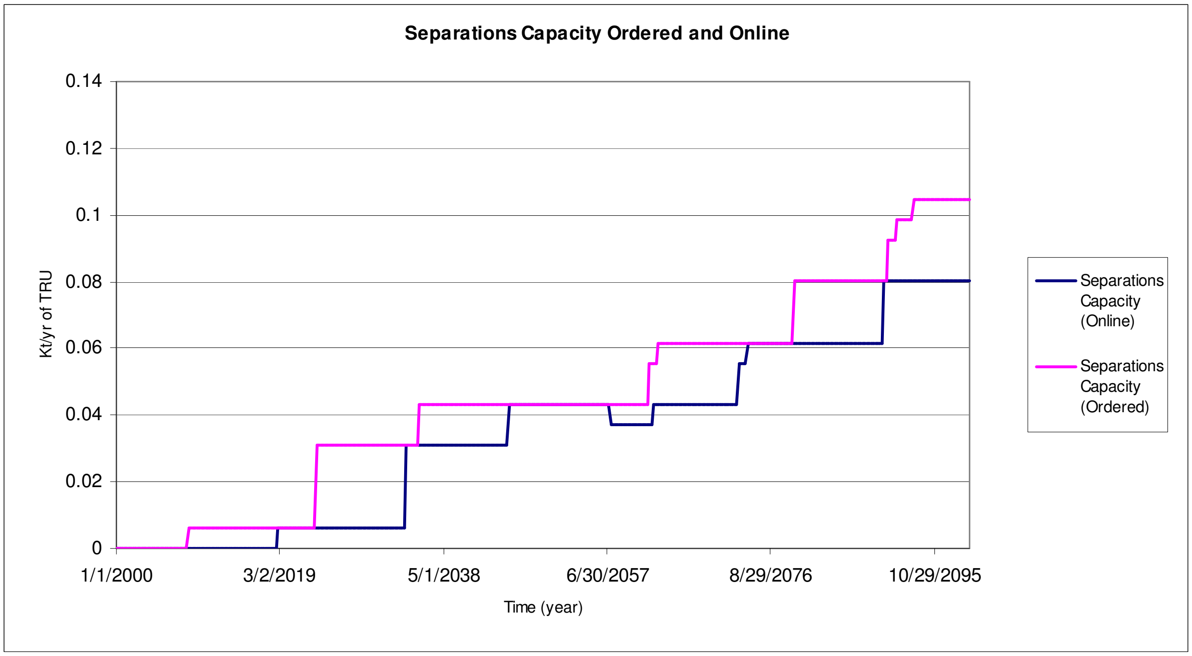

Figure 3-238: Separations Capacity with Later Delay

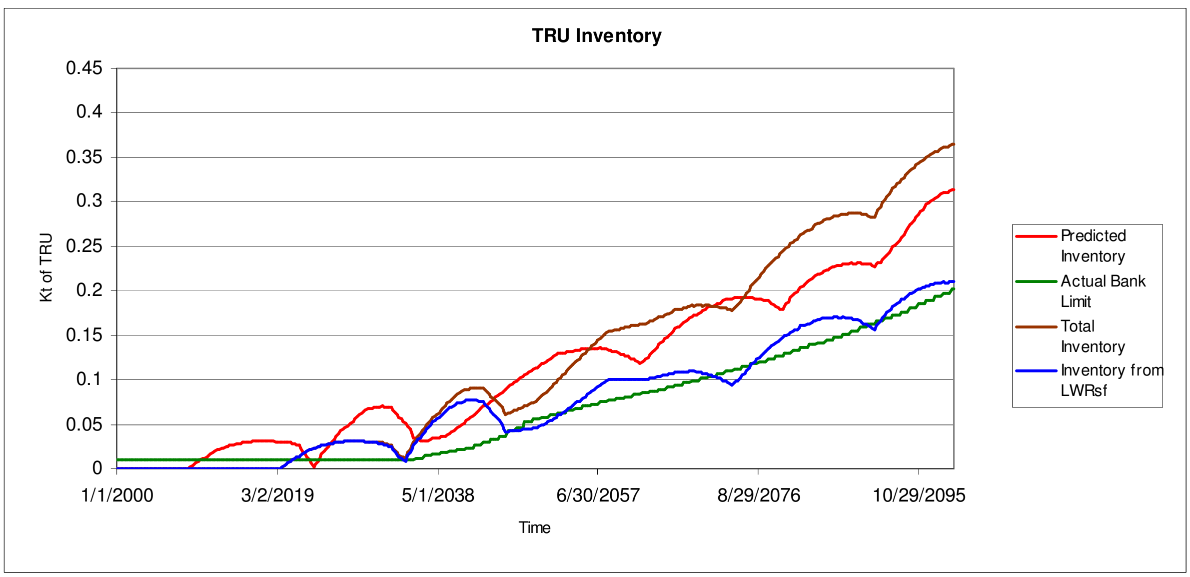

Figure 3-239: TRU Inventory with Later Delay

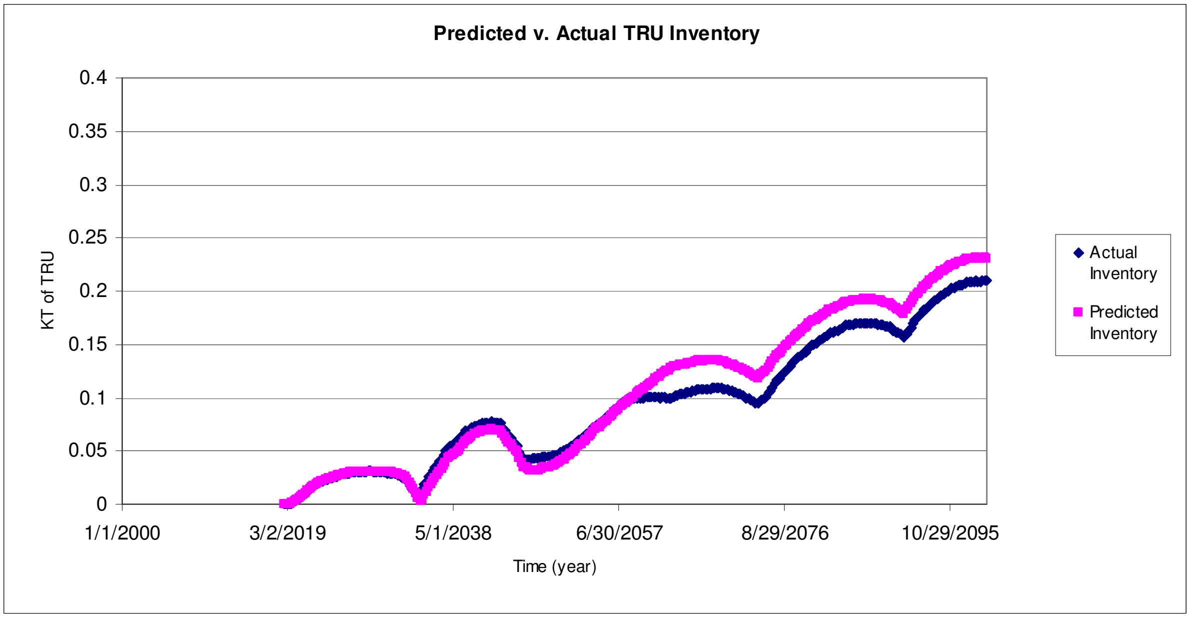

Figure 3-240: Predicted v. Actual Inventory in Later Delay

The results in this later delay show that when the facility is taken offline in year 2058 (see Figure 3-238) the simulation will use part of the bank inventory as shown in Figure 3-239. In this scenario there were no FBRs being held up because of lack of fuel resources and there were no FBRs that had to shutdown because of a lack of fuel. This analysis shows that having a bank inventory will be useful if there is a separation facility that goes offline later on in the simulation.

3.3.2.5 Summary of Separation Facility Taken Offline

In summary it was shown that when separations facilities are taken offline at the beginning severe consequences can occur as a result of FBRs not receiving their fuel supply on time. The best mitigation strategy for this event was actually to decrease separations facility sizes to 0.25 kt/yr. With this size of separation facility, two facilities are brought online at the beginning and when one facility is shut down the other one can pick up the loss capacity. Also the capacity taken offline is smaller with the smaller facilities. This conclusion is supported by analyzing the scenarios in Table 3-6 and Table 3-7. Scenario 1 and 2 in Table 3-6 have a 0.5kt/yr and 0.25kt/yr separation facility size, respectively, and for Scenario 2 there are not any FBRs that are not able to start up on time. Comparing Scenario 3 and Scenario 4 show that increasing the lead time too far beyond the recommended lead time will have negative consequences. In this comparison the lead time was increased to 5 years, from 3 year in Scenario 3, which caused the system to delay construction of new separation facilities for too long of a time (shown in Figure 3-206 and Figure 3-210). Then when the capacity was taken offline, there was a shortage of fuel and some FBRs could not start up on time. Table 3-7 shows the same results for decreasing the separation facility size and increasing the lead time. The scenarios for the 100% FBR growth case presented in Table 3-8 all have good results in terms of not having any lost FBR GWe-yr.

3.3.3 Change of Minimum Bank Limit

In the following scenarios the minimum bank limit on the separated material inventory will be changed from a one year TRU supply when at equilibrium for every operating FBR to a two year fuel supply for every operating FBR. One case from Section 3.3.1 and on case from Section 3.3.2 will be analyzed.

Delaying Separation Facility

The case that will be analyzed with a larger bank limit is Scenario 2 in Table 3-4 where the FBR growth rate is set at 20%, the separation facility size is 0.5 kt/yr, and the lead time is 4 years. The results are presented as follows.

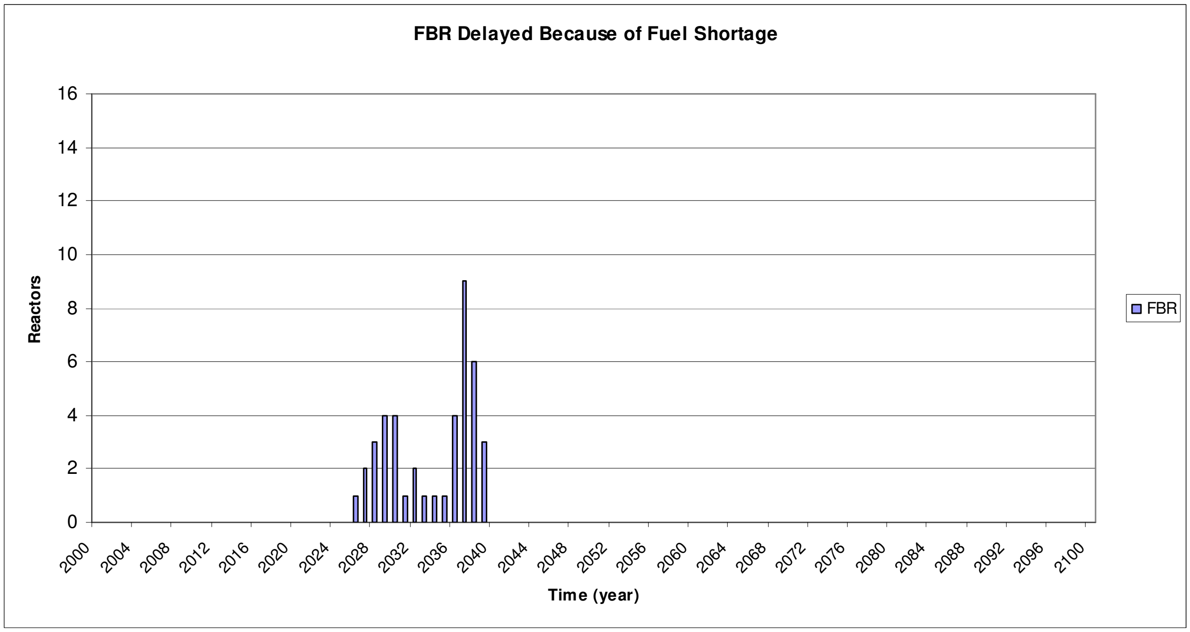

Figure 3-241: FBR Waiting to Come Online for Increased Fuel Bank and Delay Case

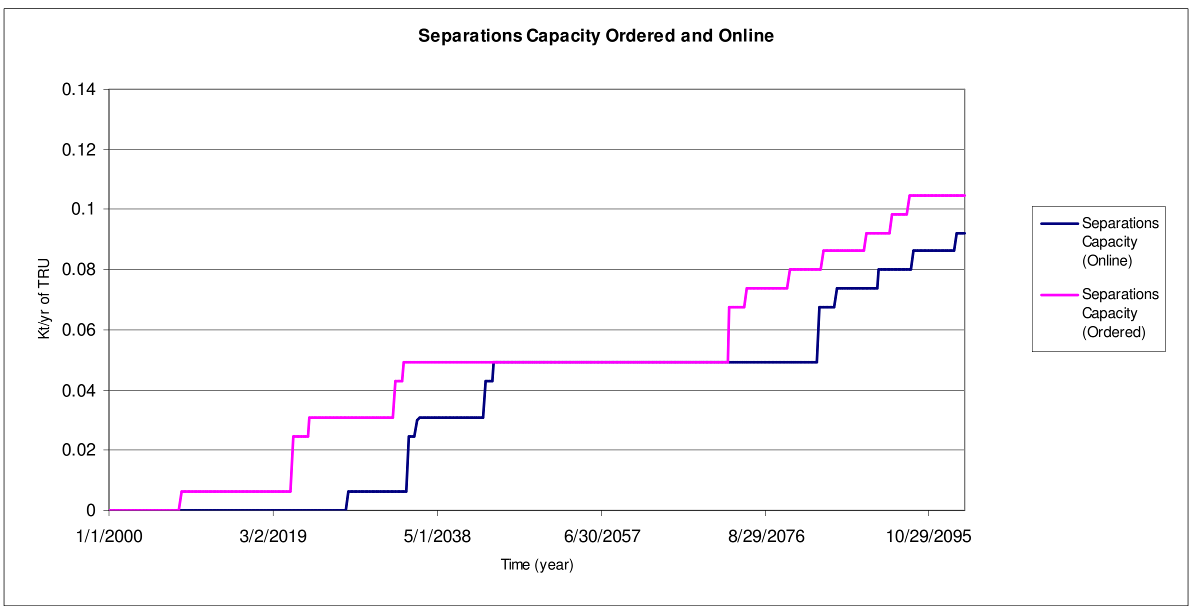

Figure 3-242: Separations Capacity for Increased Fuel Bank and Delay

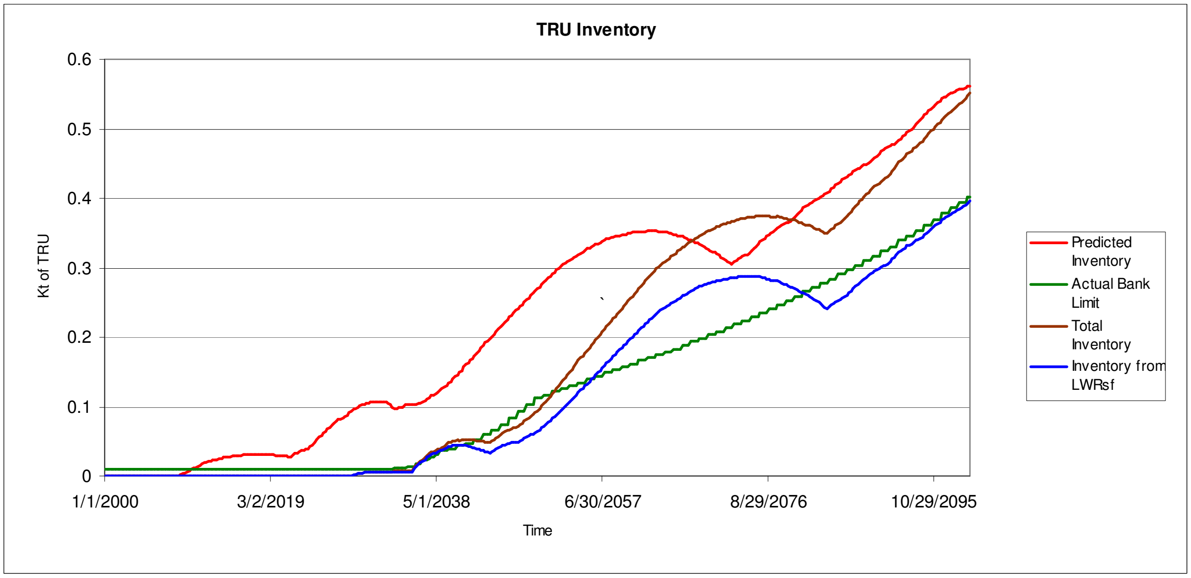

Figure 3-243: TRU Inventory for Increased Fuel Bank and Delay

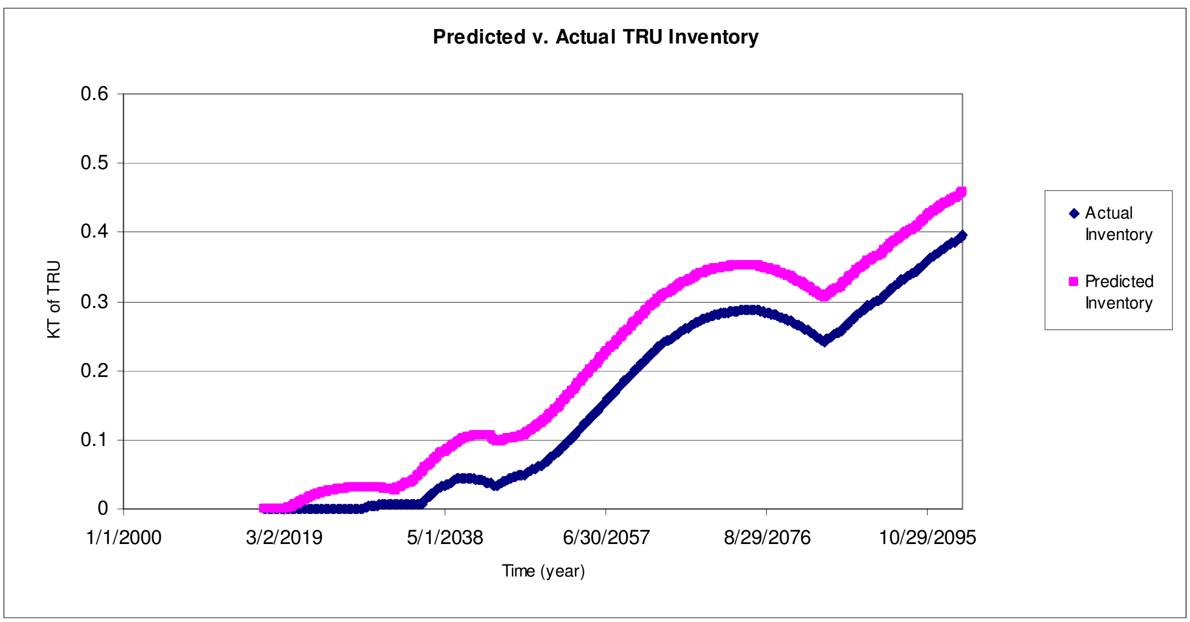

Figure 3-244: Predicted v. Actual Inventory for Increased Fuel Bank and Delay

The lost FBR GWe-yr for the new bank limit is 15.12GWe-yr, which is the same as the lost FBR GWe-yr for the decreased fuel bank case. The reason why there is no change in this GWe-yr amount is because the change in the minimum fuel bank limit has no affect for the initial facilities starting up. Figure 3-241 has the same pattern of FBRs being delayed at startup as Figure 3-175 with the lower bank limit. The only affect changing the fuel bank limit has is increasing the number of facilities that are built later on in the simulation. The build rate in Figure 3-242 is higher than the build rate for the lower bank limit shown in Figure 3-176. This causes the inventories in Figure 3-243 and Figure 3-244 to increase.

Taking One Separation Facility Offline

The case analyzed for this scenario is Scenario 1 in Table 3-7, where the FBR growth rate is held at 20%, the separation facility size is limited to 1 kt/yr, and the lead time is 1 year. Figure 3-245 - Figure 3-247 show the results of this simulation.

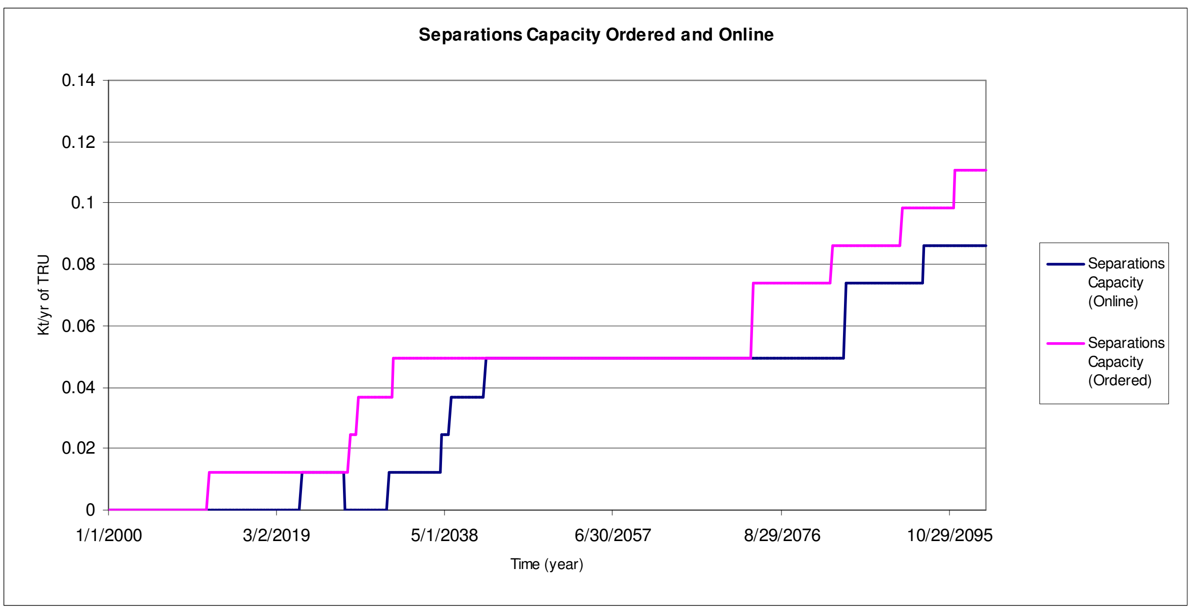

Figure 3-245: Separations Capacity for Increased Fuel Bank and Separations Offline

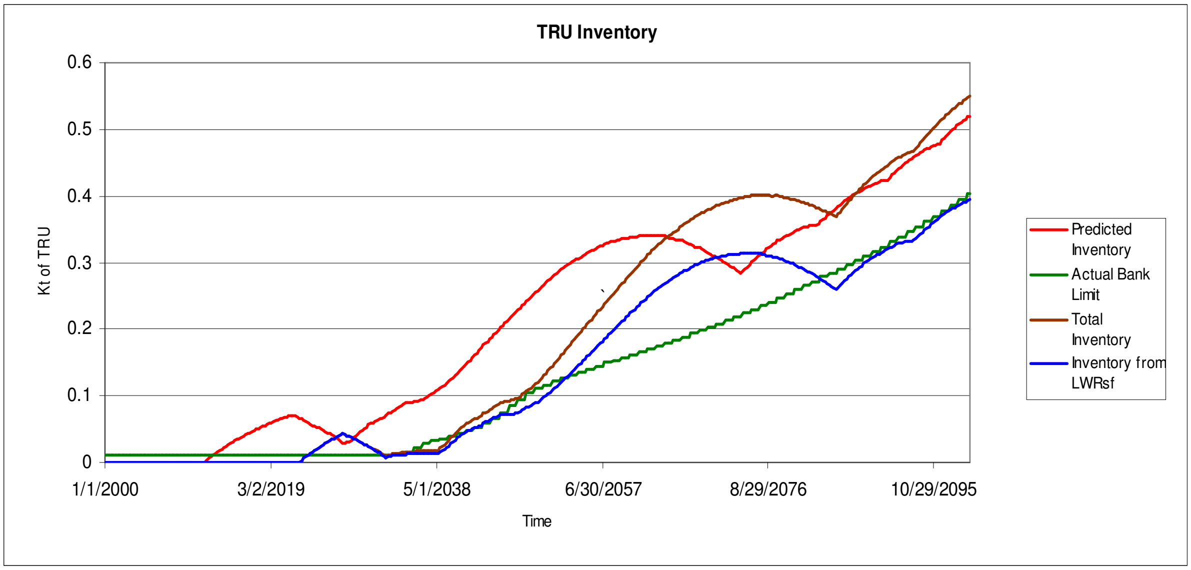

Figure 3-246: TRU Inventory for Increased Fuel Bank with Separations Offline

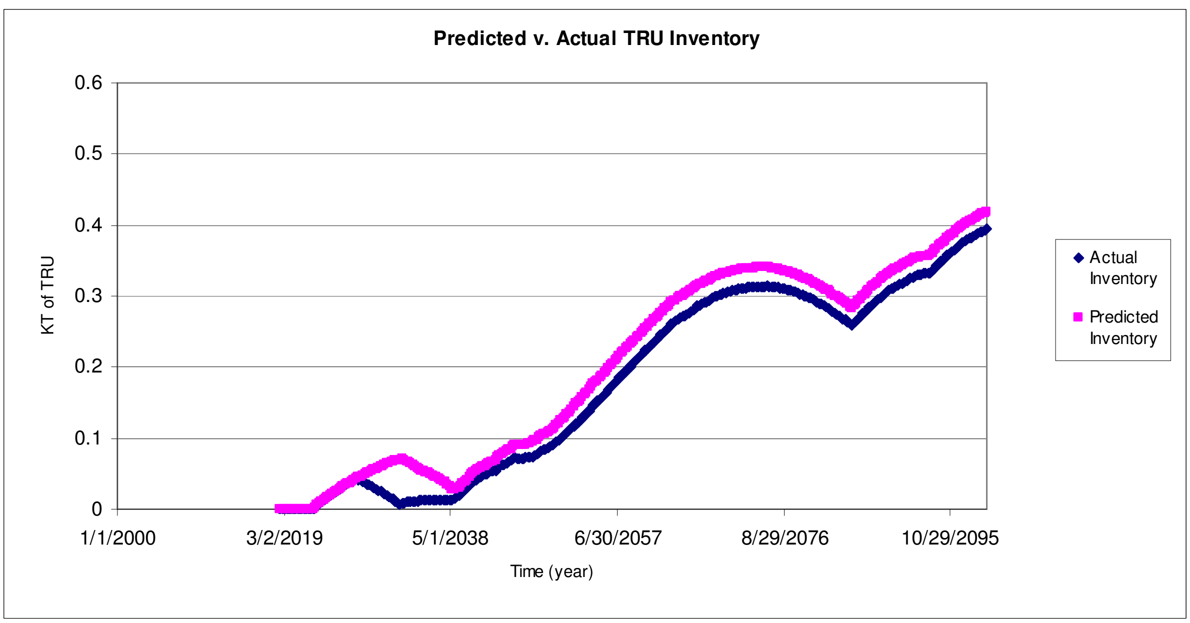

Figure 3-247: Predicted v. Actual Inventory for Increased Fuel Bank with Separations Offline

The results for the increased bank limit with 1 separation facility being taken offline show an improvement in the lost FBR GWe-yr from 1.44GWe-yr with the small bank limit and 0 GWe-yr with the larger bank limit. This is the result of the new fuel bank limit requesting new separation facilities a couple years earlier than Scenario 1 in Table 3-7. This can be seen by comparing the separation capacity graphs in Figure 3-245 and Figure 3-214. The separations capacity in Figure 3-245 has new facilities starting up right at the year 2038, while the separations capacity in Figure 3-214 has separations facilities starting up a couple of years later. This allows the system to provide fuel for those reactors in Figure 3-213 that are waiting to come online.

4 Discussion

4.1 Discussion of Results from Revised Reactor Build Methodology

The old logic for building FBRs was based around the current separated material of the system. As the simulation would step through time, it would compare the amount of separated material available to the demand from operating FBRs. If there was any excess material, then a new FBR could be ordered based on that excess capacity. This method is not very accurate in determining the full capability of the system because there is no forecasting method. The new logic will take a specified look-ahead time and calculate how much spent fuel will be available at that future date for use in a FBR. Then along with the spent fuel projection, the model will use the energy growth rate at that future date and determine how many reactors can be built. This look-ahead function allowed the model to maximize the consumption of spent fuel by maximizing the number of FBRs that can be built. Comparison of the reactor builds of Figure 3-1 and Figure 3-3, shows that with the new methodology FBRs can be ramped up during the middle of the century and then reach an equilibrium mixture between FBRs and LWRmf reactors towards the later part of the century. This equilibrium mixture is the optimum ratio of FBRs to LWRmf reactors as the energy growth continues to grow exponentially with time. The old methodology never reached this equilibrium sate because it did not incorporate a forecasting method for building reactors. This addition is very valuable to the ordering logic of the VISION model because it is a major improvement on how reactors are built. Reaching an equilibrium mixture in a fuel cycle model has been something that developers at INL, Argonne, and MIT have struggled with over the years.

4.2 Discussion of Results from Facility Ordering Methodology

The facility ordering results in Table 3-1 show how the separation facility size and the lead time are dependent upon each other. The Case 4 – 6 results in Section 3.2.2 with the 20% growth rate of FBRs have the best trend in separation facility deployment with the facility sizes that were analyzed. The 1 kt/yr separation facility size was too large for the 10% FBR growth cases and the 100% FBR growth brought on too many facilities and caused the system to have excess separations capacity. The remainder of the discussion will use the results from Case 5, which has a 20% growth rate of FBRs and a separation facility size of 0.5 kt/yr.

The overall trend in the data shows that as the separations facility size decreases the lead time needs to increase to properly control build rate and inventory. This allows the simulation to build up an inventory of separated LWRsf in order to supply fuel to FBRs for their initial core load and first few reloads, when their demand for LWRsf is at its highest level. If separations facilities are built too early with a larger than required lead time, then it will build too large of an inventory early on and further delay the construction of new separation facilities. This extended delay in constructing separation facilities then causes the system to overbuild, thus producing a larger inventory later on in the simulation. An example of this is the scenario with a lead time of 7 years, where the build rate is shown in Figure 3-91 and the inventory is shown in Figure 3-89. If separation facilities are built too late with a smaller than required lead time, then the initial inventory is too small and forces the simulation to build more separations capacity. This situation also leads to large inventories later on in the simulation. An example of this scenario is with the lead time of 1 year as shown in Figure 3-105 and Figure 3-107. It then becomes necessary to use the proper lead time with the specified separation facility size and FBR build rate. The separation facility build rate in Figure 3-99 and the inventory in Figure 3-97 with a lead time of 4 years is an example of a good build rate for separations facilities and an optimal TRU inventory level.

The optimal lead time also has implications on proliferation and economics. If large separated material inventories accumulate because of an improper lead time, then the proliferation risk is higher. Separated material is more easily used to fabricate a nuclear weapon. The economics plays a role in the sense that it is difficult to restart building facilities after a long period without any new construction. This scenario is costly as there arises new uncertainties in the construction costs. If separation facilities can be built with a steady pace then the construction costs will remain fairly constant or decrease because of the "learning curve." For these reasons it is important to understand the proper lead time and separation facility size for the given growth rate of reactors.

4.3 Discussion of Upset Scenarios

The upset scenarios that were analyzed include 1) delaying a separation facility from starting up and then 2) bringing one separation facility offline for a certain number of years.

4.3.1 Discussion of Delaying Facilities Coming Online

The cases shown in Table 3-2 have a variety of separation facility sizes and lead times. In each case the first separation facilities to be ordered are delayed in construction by 9 years. The lost FBR GWe-yr values presented in Table 3-3, Table 3-4, and Table 3-5 for the 10%, 20% and 100% FBR growth rate, respectively, are the comparable values that will determine the best scenario for handling the delay upset. The results for each of the different

FBR growth rates showed that increasing the lead time of a separation facility will help to minimize the amount of lost FBR GWe-yr.

The best mitigation strategy for this scenario may actually not be to increase the lead time or increase the separation capacity, but rather to delay the reactors from being ordered. In a more accurate simulation the reactors could simply not be ordered or delayed at a certain time in their construction. This would help to reduce the negative effects of having reactors waiting without fuel to startup.

4.3.2 Discussion of Taking One Separation Facility Offline

Each scenario that was run had one separation facility taken offline 5 years after it began operation. The facility remained offline for an additional 5 years and was then allowed to come back online. The results in Table 3-6, Table 3-7, and Table 3-8 show how the separation facility size and lead time impact the lost FBR GWe-yr. When the separation facility size is decreased it causes the overall decrease of separated material to not be as significant. In the cases where more than one separations facility starts up at the beginning of the simulation, there were no FBRs waiting to receive their start up core because the other separation facility remained in operation and the offline capacity was smaller. In the last analysis the minimum fuel bank limit was increased from 1 year to 2 years worth of fuel for each FBR. This caused the simulation to build more separations capacity early on, which helped to mitigate the negative affects from one facility being shut down for 5 years.

5 Conclusion and Recommendations

5.1 Overall Conclusion

The work presented in this thesis helped to understand many different areas of advanced nuclear fuel cycles that were previously unknown. The major addition to the fuel cycle model is the improved reactor build logic. This logic builds reactors based on a sophisticated forecasting method and will allow the model to maximum the build rate of FBRs. The second area that this research has helped understand is the relationship between the size of a separation facility, the amount of time a separation facility must start up prior to facilities requesting their services, and the number of reactors that come online in any given year. The results in this thesis showed that given these three parameters, there is an optimum facility size and lead time for building separation facilities. Lastly, this research helped to understand what effect upset scenarios on separation facilities will have on the rest of the fuel cycle. Overall, this work created a better understanding of how the different parts of an advanced fuel cycle will interact.

5.2 Future Work/Recommendations

Future work should include adding the deployment analysis to other facilities in the fuel cycle. These facilities include fuel fabrication for electro-chemical processes, fuel fabrication for aqueous processes, and separations facilities for electro-chemical processes. Variable lead times and separation facility sizes with time are also needed in order to accommodate the changing number of FBRs that come online each year. The heuristic rule of specifying the percentage of reactors by type that will meet the energy demand needs to be taken out and replaced with a more sophisticated algorithm. The current logic can have build rates for reactors that are too large. Finally, quantification of the economics and proliferation risk associated with the studies presented in this thesis should be completed.

References

1. A.M. Yacout, J.J. Jacobson, G.E. Matthern, S.J. Piet, D.E. Shropshire, C. Laws; "VISION – Verifiable Fuel Cycle Simulation of Nuclear Fuel Cycle Dynamics," Waste Management Symposium 2006, February 2006.
2. Chris Juchau and Mary Lou Dunzik Gougar. "A Review of Nuclear Fuel Cycle Systems Codes," Idaho National Laboratory, Idaho State University April 19, 2006.
3. Dole, John C.; Francis, Bruce A.; and Tannenbaum, Allen R. Feedback Control Theory. Copyright help by the authors. Macmillan Publishing Company, 1990.
4. Ford, Andrew. Modeling the Environment: An Introduction to System Dynamics Modeling of Environmental Systems. Island Press, 1999.
5. Kett P. J. et. al. "Radiological Protection and Dose Uptake in the Thermal Oxide Reprocessing Plant (Thorp)," BNFL Sellafield, United Kingdon. 1999.
6. Report to Congress – Advanced Fuel Cycle Initiative: Objectives, Approach, and Technology Summary, U.S. Department of Energy, Office of Nuclear Energy, Science, and Technology, May 2005.
7. Personal Conversations with Jake J. Jacobson, Steven J. Piet and Gretchen E. Matthern
8. Piet, Steven J. et. al. "Fuel Cycle Scenario Definition, Evaluation and Trad-Offs," Idaho National Laboratory and the Department of Energy. August 2006
9. A Summary Report of HSE's Project Assessment to Support the Consent to Restart the Thermal Oxide Reprocessing Plant (Thorp), Sellafield. Health and Safety Executive, HM Nuclear Installations Inspectorate. January 2007. http://www.hse.gov.uk/nuclear/thorp.htm

Appendices

Spent Fuel Prediction for the 2-Tier Case

This calculation is similar to that of the 1-Tier Case except all LWRsf is first sent to thermal recycle, and then after the fuel has been through the designated number of passes for thermal recycle, it can be sent to a FBR. When first starting up, the LWRmf reactor is loaded with Low Enriched Uranium (LEU) fuel. Once thermal recycled fuel begins, the shortfall in material requirement is made up by LEU. In order to predict how much MOX fuel is available for a FBR, the model will first determine when and how much MOX fuel a LWRmf reactor can produce over its lifetime and then be available for use in a FBR. This calculation starts by first calculating the number of years that a LWRmf reactor will be discharging MOX fuel after a specified number of thermal recycles or passes, which is given as follows:

$$\Delta T_{MOX}^{P} = \Delta t_{LWRmf}^{Lifetime} - P\left(\Delta t_{ws}^{LWRmf} + \Delta t_{S}^{LWRmf} + \Delta t_{FF}^{LWRmf} + \Delta t_{cycle}^{LWRmf} * B\right) - \Delta t_{cycle}^{LWRmf} \quad \text{Equation 2.33}$$

The next step in the calculation is to calculate the fraction of MOX fuel in each batch of fuel that is in the final pass in a LWRmf. This is calculated by dividing the amount of spent fuel from the previous pass by the amount of fresh fuel for the next pass. This ratio is calculated in Equation 2.34:

$$f_{MOX}^{P} = \prod_{p=0}^{P} \frac{FL_{LWRmf_{SF}}^{p-1} * w\%_{LWRsf}^{p-1}[PuControl]}{FL_{LWRmf_{Fresh}}^{p} * w\%_{LWRmf_{Fresh}}^{p}[PuControl]} \quad \text{Equation 2.34}$$

The P in Equation 2.33 and Equation 2.34 is equal to the maximum number of thermal recycle passes. After the fraction of final pass spent fuel is calculated, the next step is to calculate the number of equivalent full MOX batches of final pass fuel that a LWRmf reactor will discharge over its lifetime. Since a yearly cycle will discharge one batch per year, this is done using Equation 2.35:

$$B_{MOX}^{P} = \Delta T_{MOX} * f_{MOX} \qquad \text{Equation 2.35}$$

The variable B_{MOX}^{P} is dependent on the number of thermal recycle passes and cycle time. After the number of MOX batches are known, Equation 2.7 must be revised to include the amount of time before a FBR can use MOX recycled fuel. The new ΔT_{look} is as follows:

$$\Delta T_{look} = \Delta t_{look} - \left(\Delta t_{LWRmf}^{Lifetime} - \Delta T_{MOX}^{P} + \left(\Delta t_{ws}^{LWRmf} + \Delta t_{S}^{LWRmf} + \Delta t_{FF}^{FBR} \right) \right) \qquad \text{Equation 2.36}$$

Now that the total number of MOX batches for any given LWRmf reactors and the look ahead time to account for MOX spent fuel is known, the amount of spent fuel from thermal recycle that can go to fuel FBRs can be calculated using Equation 2.37:

$$SF_{MOX,t+\Delta t_{look}}^{P} = RO_{LWRmf}^{t+\Delta T_{look}} * B_{MOX}^{P} * FL_{LWRmf}^{P} * w\%_{LWRsf}^{P} \qquad \text{Equation 2.37}$$

$SF_{MOX,t+\Delta t_{look}}^{P}$ is then used to create a new Spent Fuel Stock, which is similar to the $\overline{SF}$ found in Equation 2.10. The new Spent Fuel Stock is as follows:

$$\overline{uSF_{t}} = \overline{uSF}_{t-1} + SF_{MOX,t+\Delta t_{look}}^{P} \qquad \text{Equation 2.38}$$