Contract No.:

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Fusion Fuel Cycle Inventory Reduction Studies using a Processing Time based Discrete-Time Interval Model

Developing a Fusion Pilot Plant (FPP) design that minimizes risks due to tritium in-process inventory is an important concern for the operation of commercial devices. This becomes even more of concern since an FPP will be breeding more tritium than is burned in the reactor for sustainability. The in-process inventory (IPI) is the tritium moving through the system that is not in the storage and delivery sub-system. A process model that solves time-dependent differential equations based on processing times was used to investigate the reduction of IPI of a potential fuel cycle design. The impact of new and more efficient technologies such as Direct Internal Recycling (DIR), Metal Foil Pumps (MFP), Continuous Pumping (CP), improved Isotope Separation (IS), and hydrogen separating continuous pumps (HSCPs) on IPI was investigated by adjusting sub-system processing-times and material flow streams. It was shown that any of the insertions of DIR studied in this paper caused a reduction in the total IPI of the system and proved to be the optimal way to reduce IPI in the system. Fuel cycle modifications near the torus, such as a coupled DIR and improved pumping systems, produced the largest reductions in tritium inventory.

Keywords: fusion, fuel cycle, tritium, inventory, direct internal recycling

I. Introduction

Conversations around the commercialization of fusion energy have grown over the past several years with facilities racing to determine the first design of a Fusion Pilot Plant (FPP).[1-3] A FPP will be designed in such a way that it will produce net electricity, while satisfying safety and regulatory concerns. The leading fuel for a FPP will be deuterium-tritium (D-T), and the risks associated with a D-T fuel cycle must be minimized.[4] Since tritium is a radioactive material the quantity present in the fuel cycle and on the FPP site will be regulated,[5] making the in-process inventory of tritium a key concern for an FPP design. This becomes even more of concern since an FPP will be breeding more tritium than is burned in the reactor for sustainability. An FPP will require an initial tritium inventory to start operations and will cycle tritium through a series of sub-systems that are grouped into the reactor and the tritium plant.

It is essential to understand the sub-systems and design of the tritium plant in conjunction with the torus vessel.[6,7,8] Having the capability to identify what sub-systems are occupied with high concentrations of tritium in-process inventory (IPI) can help reduce the tritium inventory in the system. This can be done by either introducing new or efficient technology or alternative material flow streams. To investigate the potential reduction of tritium inventory in a FPP fuel cycle, it is proposed in this paper to use a fuel cycle discrete-time model that calculates the inventories of sub-systems by solving time-dependent differential equations based on processing times.

II. Fuel Cycle Design

Figure 1 is a block diagram of a potential FPP fuel cycle design with indicated material flow streams (arrows). This diagram is a visual representation of the inputs passed to the time-dependent fuel cycle model used to calculate inventories. Each sub-system or block within the fuel cycle has an associated processing time (T_i), fractional flow from connecting component(s) ($F_{j\rightarrow i}$), and an initial inventory (I_{i_0}). All components have an initial inventory or initial process inventory equal to zero except for Storage and Delivery (SD), $I_{6_0} = 10\ kg$.

Flow of tritium starts from the SD subsystem, which then supplies tritium to the Fueling (F) sub-system. F injects $\dot{m} = \frac{\dot{N}^-}{\beta}\frac{g}{day}$ of tritium into the Plasma Vessel (PV), where β is the tritium burn faction and $\dot{N}^-$ is the burn rate in g/day. In this work the fueling efficiency is absorbed into β. The injection rate, $\dot{m}$, is chosen based on the desired power output, which is proportional to $\dot{N}^-$. This is the minimum amount of tritium required to be injected into the plasma to increase the probability of the desired power output. Tritium in the PV is either burned up, moves through the fuel cycle to Exhaust Pumping (EP), or permeates through to the coolant loop, indicated by the Helium Coolant Loop. The tritium that is burned releases 14 MeV neutrons that pass through to the Breeder (Br), which has a production rate of tritium equal to $\dot{N}^+ = \Lambda\dot{N}^-$ where Λ is the tritium breeding ratio. The sub-systems are numerically labeled in such a way that the systems code can identify connecting components. The order of sub-system label is arbitrary for the system code, meaning that SD could easily be labeled 12, as long as, the input file indicates that Fueling (7) is getting flow from SD (12).

The scripted model is also adjustable based on the sub-systems included and their material streams. For example, SD has the option to receive flow from both the Exhaust Pumping (EP) and Exhaust Processing Palladium (Pd) Diffuser (EPPD). The amount of flow from these sub-systems to SD is controlled by their respective fractional flow, $F_{8\rightarrow6}$ or $F_{9\rightarrow6}$. A detailed description of the time-dependent fuel cycle model has been explained in a prior work.[9]

The fuel cycle model can be used to investiage the impact on tritium IPI when introducing new or more-efficient technology and alternative flow streams.

Identifying areas of potential improvement can lead to safety-aware fuel cycle design choices early in the commercialization process. Since the fuel cycle model depends on several parameters it is important to understand how each affects the time-dependent calculation of inventory and explain what these changes in parameters mean for the fuel cycle design. In the following sub-sections, the effect of T_i, I_{6_0}, and $F_{j \to i}$ will be described and evaluated.

Figure 2 is the block diagram of the fuel cycle studied in this project, but it now includes numerical input information relevant to the process model. In each component or block there is a fast-processing time, $T_{i_{fast}}$, that will be referred to as the ITER relevant processing times[10-14] and a slow processing time, T_{i_slow}.[15] The ITER relevant processing times are anywhere from 2 to 1×10^5 times faster than T_{i_slow} and will be used in sub-section II.A to demonstrate the difference in inventory when you have a system that quickly reaches steady-state and when you have a system that takes longer to reach steady-state. The term fast is used for the ITER relevant case to draw attention to the change in inventory when steady-state is reached rapidly; however, this is not a limit on how fast the processing times can be for each sub-system. Section III will make use of even faster processing times that simulate the use of improved or more efficient technology then what is used in the ITER relevant case. The arrows between sub-systems represent material flow streams and when the arrows are split this means that the sub-system feeds two or more other sub-systems. The amount of inventory that flows along these material streams are determined by the fractional flows, denoted as percentages in the figure. For sub-systems that only feed a single component the fractional flow is 1.00 or

100% and for the dashed arrows the fractional flow is temporarily zero. The re-routing of flow streams along the dashed arrows to reduce IPI is known as Direct Internal Recycling (DIR) and will be introduced in sub-section 2.3.

Included also are source terms that indicate the Breeder production rate ($\Lambda\dot{N}^{-}$) that enters the Blanket Loop (BL) and the amount of flow rate ($0.1\frac{g}{day}$) that enters the IS from H2O Processing (H2OP). Table I details the values used for each parameter in this study except for when explicately stated otherwise. For the burn rate chosen in this paper (78.767 g/day) the power output would be roughly 513 MW.

II.A Processing Times, T_i

The processing time or T_i of a component within a fuel cycle determines how long that sub-system takes to process the tritium internally. The inventory within the sub-system reaches steady-state at a rate proportional to its processing time multiplied by the summation of flows entering that sub-system, as shown in Equation (1).

$$\dot{I}_i = 0;\ I_i = \left(\frac{T_i}{F_{loss}}\right)(S_i + \sum \frac{F_{j\to i}}{T_j} I_j) \qquad \text{Equation (1)}$$

Where $F_{loss} = (1 + \epsilon_i + \lambda T_i)$, ϵ_i *is* the fractional loss due to non-radioactive decay, S_i is the tritium source term, and λ is the radioactive decay constant ($\lambda = 1.54 \times 10^{-4}\ days^{-1}$). S_i is equal to zero for most components and is denoted by a combination of terms such as the production rate ($\Lambda\dot{N}^{-}$), which is the source term for the Blanket (Bl). For the SD sub-system, the above equation must be modified to account for a processing time of zero. This is because SD is considered a type of tank that does not have any sort of internal processing involved with it and the main loss is due to the radioactive decay of tritium. As can be seen in Equation (1) the smaller the processing time the faster that component reaches steady-state and the lower the inventory in that sub-system. For components with a single flow in or a source flow in, such as EP and the Bl, the difference in inventory between the ITER relevant and slow processing times is clearly visible. Figure 3 compares the calculated IPI between three separate sub-systems at the ITER relevant (solid) and slow (dotted) processing times. For the ITER relevant case, steady-state is reached rapidly and the IPI in each sub-system starts out lower or is eventually lower than the slow case.

For sub-systems that have inlets from multiple other sub-systems, such as IS, the overall impact of T_i on IPI is less clear. The steady-state inventory is also proportional to the summation of flows entering that sub-system and hence inversely proportional to their processing times, T_j. If the feeding sub-system has a high processing time, then there is low inventory flow into the sub-system of interest. This will show as a reduction of IPI but there will still be an increase in inventory in the other sub-systems. The slow rise in the IPI of the IS sub-system is a demonstration of this occurring. Even though it is apparent in both cases, it is more prevalent in the slow processing time case where the sub-systems that feed into the IS have processing times of $T_1 = 1.00\ day$, $T_2 = 100\ days$, $T_{10} = 1.00\ day$, and $T_{11} = 1.00\ day$. Before the sub-systems equilibrate there is build-up of IPI in these feeding sub-systems that show as a low IPI in the IS and a shift in the IS steady-state time. Eventually the IS sub-system reaches steady-state and has a higher IPI than the ITER relevant case.

Adjusting T_i in the fuel cycle for different components can indicate a new or more-efficient technology. Observations can be made on the impact of these specific technologies to the in-process inventory and identify where it is most beneficial to the fusion fuel cycle. When applying this technique to specific sub-systems such as the IS, EP, and the Bl, changes in inventory can readily indicate improvements to the system. If a sub-system is made more efficient, then the tritium will pass through the fuel cycle quickly and reduce the amount of build-up in that sub-system, and hence, a reduction in the total IPI. Also, there could be potential for improved benefits if changes in T_i are coupled with other adjustments to the fuel cycle, which will be discussed further in sub-section III.B.

II.B Initial Cache Inventory, I_{6_0}

The total IPI is the amount of tritium that is flowing through all sub-systems in the fuel cycle minus SD. The cache inventory is the inventory in the SD sub-system and is denoted I_6 and the initial cache inventory is denoted I_{6_0}. Figure 4 shows the time-dependent cache inventories calculated for different values of I_{6_0} for the ITER relevant and the slow processing-time case. For the ITER relevant case the SD sub-system depletes to about 400 g less than the initial cache inventory before recovery. The recovery of tritium inventory comes from both the return flow from the main loop (from IS) and new tritium from the breeder loop. This holds for both values of I_{6_0} in the ITER relevant case since the processing-times are fast enough to move tritium through the system and maintain a positive cache inventory.

For the slow T_i case, a larger I_{6_0} is required to maintain inventory in the SD sub-system. This is because large inventories of tritium are being held up in in-process sub-systems due to the much higher processing times. The $I_{6_0} = 10{,}000\ g$ (magenta) shows this trend clearly in the fast full depletion of the SD sub-system. This shows that the slow case fuel cycle is unsustainable for a 10,000 g initial inventory. The initial inventory is not sufficient to supply the process. Even with a 35,000 g initial inventory, it takes considerably more time to see the flow from the in-process sub-systems and the breeder loop and the long-term sustainability of the fuel cycle is doubtful since the tritium from breeding does not make up for the lost inventory.

This means that the amount of inventory in the SD is a strong indicator of how much tritium is present in the system. The more cache inventory the less in-process inventory when dealing with reasonable processing-times. This means that if in-process inventory can be re-routed or directed to the SD sub-system there will be a reduction of IPI. Furthermore, since the slow processing-times are unreasonable and require a >3.5× increase in initial cache inventory, the remainder of this study will utilize the ITER relevant processing times detailed in Figure 2 unless stated otherwise.

II.C Fractional Flows, $F_{j\rightarrow i}$

The fractional flow, $F_{j\rightarrow i}$, determines the quantity of inventory that flows from one sub-system, j, to a second sub-system, i. When sub-system j is only feeding a single component then $F_{j\rightarrow i} = 1.00$. This is equivalent to indicating that 100% of the flow moves from sub-system j to sub-system i. An example of $F_{j\rightarrow i}$, the

BE sub-system feeds the Blanket Heat Exchanger (BHE), IS, and SD. The fractional flow is split between each of these systems with $F_{1\to4} = 0.05$, $F_{1\to6} = 0.05$, and $F_{1\to5} = 0.90$. The components connected by a dashed line have an $F_{j\to i} = 0$.

Adjusting the fractional flows within the system allows exploration of alternative material flow streams and potential new or more efficient technology. For a single sub-system that feeds multiple sub-systems, if a higher fraction of inventory is moved along one stream, then the fraction moving along the other streams decreases. Altering the route of inventory in the system can potentially reduce tritium inventory in sub-systems notorious for high tritium inventory, such as the IS. This relationship can be seen in Equation (1). If a sub-systems incoming fractional flow is decreased, then the IPI for that sub-system is decreased.

The addition of DIR can potentially reduce the total IPI. DIR utilizes pump technology that is coupled with diffusion or hydrogen separation. This allows for a fraction of the exhaust from the plasma vessel to be transferred directly from the EP or EPPD to SD and bypass IS effectively reducing the total IPI. This technology can be explored by adjusting the fractional flows in the process model. Figure 5 shows that when a fraction of the inventory flows from EP to SD ($F_{9\to6}$) there is a reduction in inventory after 365 days in the total IPI and IS that is dependent on the fractional flow between the two sub-systems ($F_{9\to6}$). The Baseline is the unaltered system shown in this paper without DIR ($F_{9\to6} = 0$). Each bar to the right of the baseline has an increasing percentage of DIR from EP to Fueling ($F_{9\to7}$) from 20% to 90%. As this fraction increases the total (peach) and IS sub-system IPI is reduced. The fractional flow from EPPD ($F_{9\rightarrow10}$) decreases as DIR percentage increases.

III. IPI Reduction Technology

There are changes to sub-systems and overall design that can potentially improve upon the fuel cycle and offer a reduced total IPI. The reduction of IPI in the fuel cycle is of key importance because tritium is a scarce and radioactive material. Reducing the in-process inventory improves accountancy opportunities and minimizes the risks associated with a DT fuel cycle. The demonstration of reducing in-process inventory by re-routing flow through DIR encourages the investigation of other options to reduce total in-process inventory. This section will compare the different opportunities of improvement to reduce the in-process inventory of the system to the Baseline parameters and technologies. The following potential areas of improvement will be discussed:

1. **IS/4:** This is the reduction of the IS processing time by a factor of four, $T_5 = \frac{0.056\, days}{4} = 0.014\ days$ and represents technical advancement in the IS sub-system. Here, a 4× reduction in IS processing time is proposed as an ambitious but conceivable goal of a vigorous research program in isotope separation and is not motivated by any specific technology or improvement pathway.
2. **CP:** The Continuous Pumping (CP) is a replacement for the batch process and is represented as a reduction of the EP processing time by a rough factor of 100, $T_8 = \frac{0.035\, days}{100} = 0.00035\ days$.

3. **MFP:** The inclusion of a Metal Foil Pump (MFP) as the EP. Adding the MFP to the fuel cycle is a form of DIR where 90% of the flow passes from the EP to SD.
4. **Pd_DIR:** 90% of the inventory moves from EPPD to SD.

Combinations of the methods will be investigated in sub-section III.B, as well, to observe the preferred options to reduce in-process inventory.

III.A Comparing Single Changes to the System

The four process model adjustments mentioned at the top of Section 3 target three potential areas of improvement: the IS sub-system, the EP sub-system, and DIR. Since the IS sub-system is notorious for retaining high tritium inventory, exploring options that reduce this sub-system's inventory is of interest. This can be done by decreasing the IS sub-systems processing time, T_i, effectively modeling a more efficient IS sub-system or by by-passing the sub-system through some form of DIR. DIR can be implemented either by re-directing a fraction of the flow from EPPD to SD (Pd_DIR) or from EP to SD (MFP). The MFP is designed in such a way that it is effective at separating and pumping hydrogenic species.[16] The pump would be placed near the torus and separate out the fueling gas from other gases with a reduced processing time.[17]

Improvements in the exhaust pumping system (EP) can be made as well. The fuel cycle concept introduced in this paper has a Baseline EP equivalent to a batch pump. Batch pumps are slow since they process in batches, so one batch must be processed before the second batch can process and so on for any following batches. If a continuous pump (CP) is used to replace the batch pump, then the amount of time the in-process inventory spends in EP decreases. This can be represented in the model by decreasing the EP T_i.

Figure 6 shows the calculated total IPI and the IPI for both the IS and EP sub-system after 365 days of operation. The inventories calculated are after implementing one of the four in-process inventory reduction methods and the Baseline. The total IPI indicates an overall improvement to the system, whereas the IPI of the IS and EP shows the more direct impact of the changes in the system. This is especially clear when observing the EP IPI of the CP modifier that has been reduced below the current scale of the figure. Each implementation reduces the total IPI of the system.

If updates to the fuel cycle were limited to a single modification to reduce the total IPI of the system, the MFP is an optimal choice from this analysis. This is expected because the MFP will be placed at the earliest point of insertion for improvement, which is nearest the torus. In addition, the MFP separates and routes 90% of the fuel directly to SD, reducing inventory that is tied up in other sub-systems such as IS. The implementation of MFP within the fuel cycle introduced in this paper reduces the total IP of the system by a factor of 2. It is also worthwhile to note that DIR through PD diffusers offers similar improvements in IPI as MFP, with only a 4.5% difference in IPI.

The other changes also made some improvement in the total IPI by impacting a specific sub-system. For example, when reducing the processing time of the IS sub-system there is a reduction in the total IPI. This is caused by an almost factor of four reduction of IPI in the IS sub-system, which is proportional to the change made to the sub-systems processing time. The proportionality is because the sub-system has reached steady-state at 365 days. The next sub-section investigates the opportunity to combine different improvements to the system.

III.B Comparing Combinations of Changes

The design changes and potential improvements of the fuel cycle are not limited to a single change; therefore, it is of interest to investigate combinations of the modifiers introduced. Currently, there are no significant technical barriers to the implementation of DIR from the EPPD to SD (PD_DIR) since Pd diffusers are a well-established technology. Therefore, this will be made the new Baseline for comparison. Even though the MFP was determined the optimal single solution for improvement to the fuel cycle its technical readiness level is still low, but combinations using the MFP will still be explored. One such combination, MFP + CP, is of key interest because it represents hydrogen separation and continuous pumping as a combined unit (referred to HSCP in this paper). One example of such a system is a 'Snail' pump, which gets its name from the unique regenerative 'Snail' head that continuously removes frozen hydrogen from the cryo-condensation surface while the pump is active.[12, 18] This allows for the fast separation and pumping of hydrogenic species to the SD nearest the torus. It is also worthwhile to note that the MFP+CP combination is the preferred choice for the EU DEMO via the KALPUREX process. [19]

Figure 7 shows the calculated total IPI and IPI of the IS and EP sub-systems after 365 days of operation. The inventories are calculated using combinations of modifiers and the new baseline, which only has the DIR from the EPPD to SD (PD_DIR) active in the fuel cycle. Any of the modifiers that include MFP are in combination with the old Baseline. This also includes the HSCP term since describes the combination of MFP + CP.

As expected, any of the modifiers that include MFP demonstrate a reduction in IPI. The HSCP implementation with IS/4 shows the highest decrease in total IPI and the individual sub-systems. This also implies that when changes can be made earlier in the cycle the higher the reduction in the total IPI. The HSCP is the implementation of MFP and CP, which are both modifications near the torus. In fact, when either of the DIR are coupled with CP the lowest in-process inventories are realized. This shows that DIR is an excellent asset to reducing the in-process tritium inventory. But it also implies that improvements to the torus exhaust processing system, specifically the development of some form of continuous pumping, can contribute to the reduction of in-process tritium in the system. With the new baseline, the greatest inventory reduction for a single change occurs with continuous pump development (CP).

It is important to note that the IPI of the sub-systems between EP and IS are not included in the figures, but a reduction of inventory in these sub-systems will contribute to a reduction in the total IPI. For CP + IS/4 and HSCP + IS/4, there is not a difference between the IPI of EP and IS but the total IPI is different. This is because HSCP diverts a larger fraction of flow from the EP toward the SD, than the change in processing time for CP. Both modifiers reduce the flow into sub-systems downstream of the EP with the HSCP + IS/4 reducing the IPI ~15% more than the CP + IS/4.

IV. Conclusion

A discrete-time processing time based fuel cycle model was developed and used to simulate changes in fusion fuel cycle sub-system technology and efficiency. Simulations of improvements in the isotope separation sub-system, in the exhaust processing sub-system, and through direct internal recycling were performed by adjusting the processing times (T_i) and fractional flows ($F_{j \to i}$) in the model. The goal of the simulations was to investigate the changes of tritium in-process inventory and identify areas of improvement that could potentially reduce tritium inventory in the fuel cycle. The information obtain supports fusion fuel cycle design decisions and facilitates decisions on research and development focus areas.

The discrete-time model analysis demonstrated that when modifications are implemented early in the fuel cycle, nearest the torus, the highest reduction in in-process inventory can be realized. For both the single implementation and coupled implementation of modifiers, direct internal recycle combined with continuous pumping proved to be the optimal way to reduce in-process inventory in the system. Whether directed from the exhaust pumping or through metal foil pumps, directly recycling the fuel demonstrated the highest reduction in the total inventories in the system. The continuous re-routing of a fraction of fuel from the exhaust system to the storage and delivery reduces the possible tritium inventory in in-process sub-systems downstream. Research efforts should be encouraged to bring up the technical readiness level of continuous pumps and direct recycling for implementation in commercial devices in order to reduce both start-up and in-process inventories.

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Tables and Figures

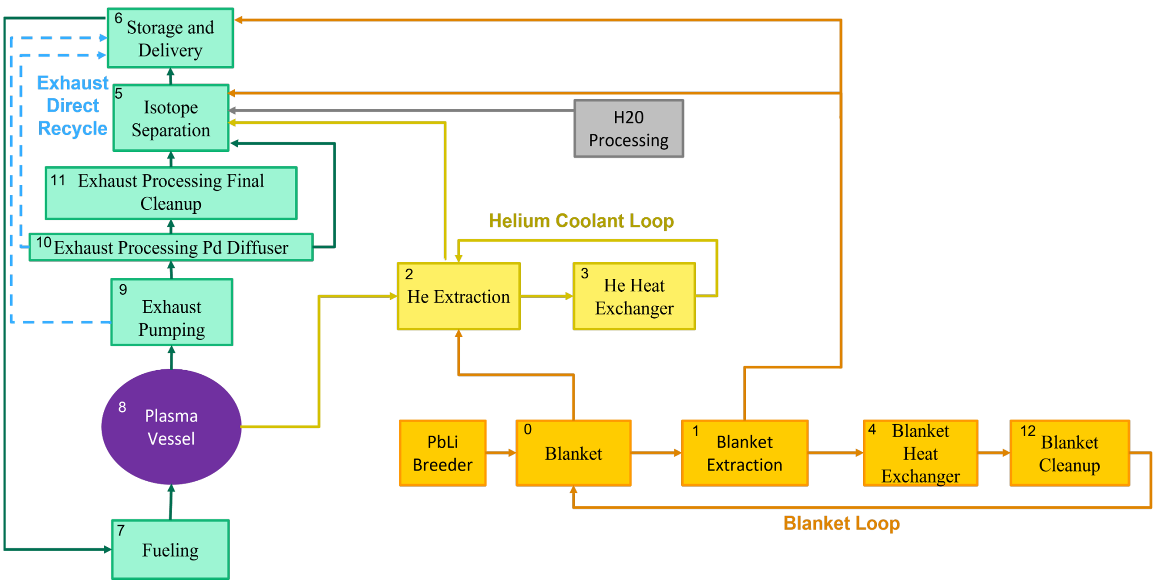

Figure 1. Block diagram model of a potential FPP fuel cycle with optional Direct Internal Recycling (DIR) included as the dashed material flow streams.

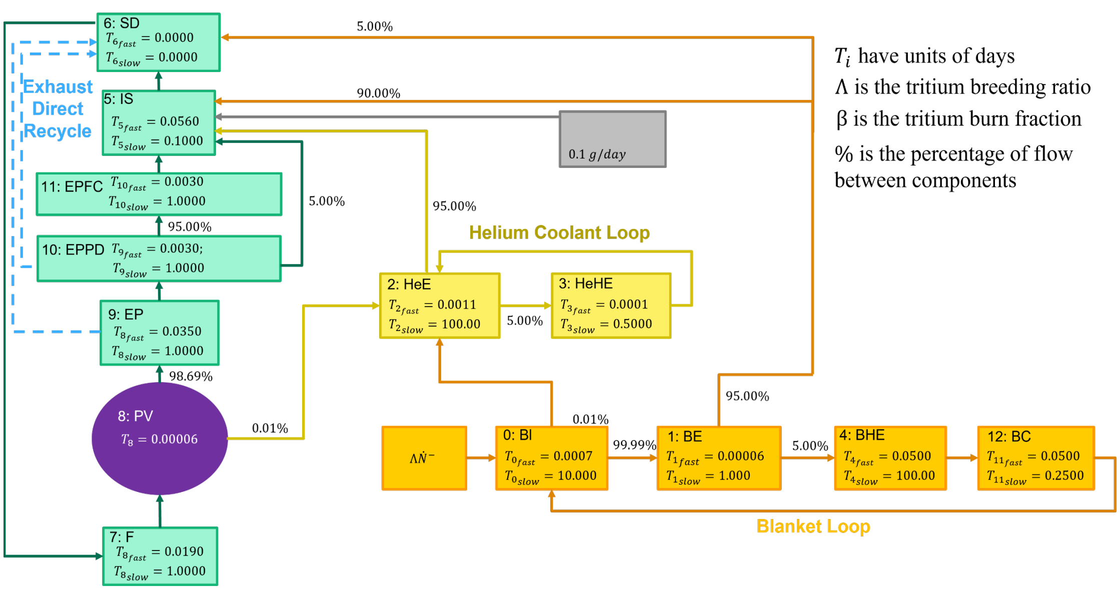

Figure 2. A Block diagram model of a potential FPP fuel cycle with optional Direct Internal Recycling (DIR) included as the dashed material flow streams. Also shown are the respective processing times for a fast fuel cycle system ($T_{i_{fast}}$) and a slow fuel cycle system ($T_{i_{slow}}$) and the fractional flow (%) between components. If the component contributes to only one other component, then its fractional flow is 100%.

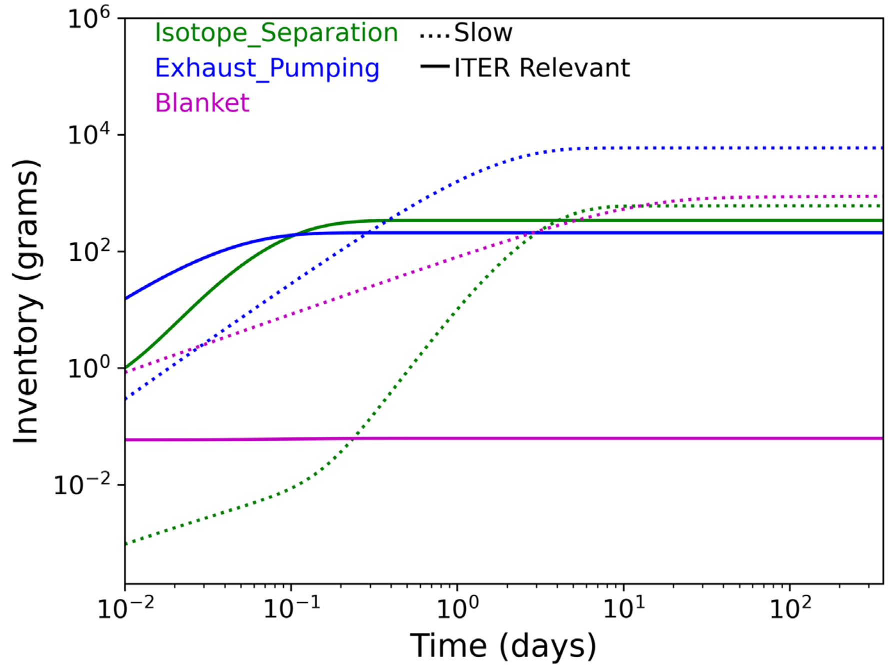

Figure 3. Calculated time-dependent inventories for fast (solid) and slow (dotted) processing times. The three sub-systems in the fuel cycle are Isotope Separation (green), Exhaust Pumping (blue), and the Blanket (magenta).

Table I. Values used to calculate the covariance prediction

Λ	Tritium Breeding Ratio	1.068[7,20,21]
β	Tritium Burn Fraction	0.013[7,20]
$\dot{N}^{-}$	Tritium Burn Rate (g/day)	78.767
I_{60}	Process Inventory (g)	10,000

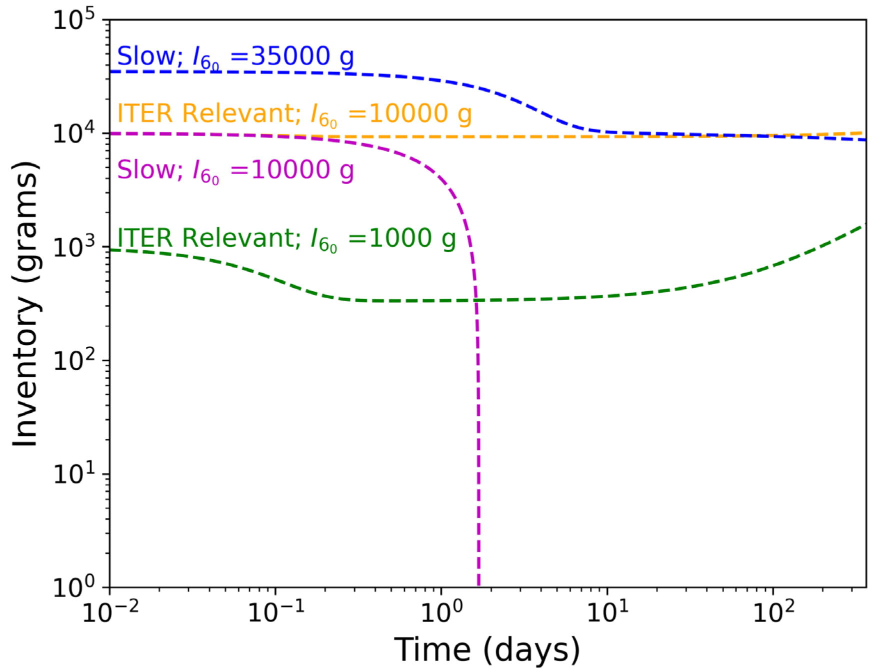

Figure 4. The calculated cache inventory, I_6, for different initial cache inventories, I_{6_0}, in the SD sub-system for the ITER relevant and slow processing-time case. When the movement of tritium through the system is slow most of the tritium inventory is held up in in-process sub-systems.

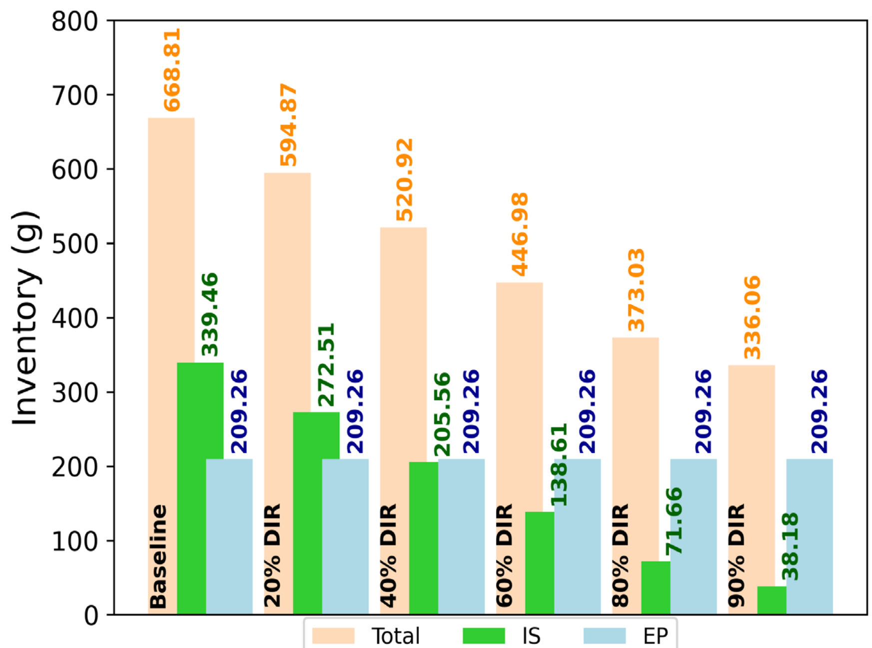

Figure 5. Calculated IPI after 365 days for the total IS and EP sub-systems with Baseline (left), 20% DIR, 40% DIR, 60% DIR, 80% DIR, and 90% DIR fractional flows from the EP to SD.

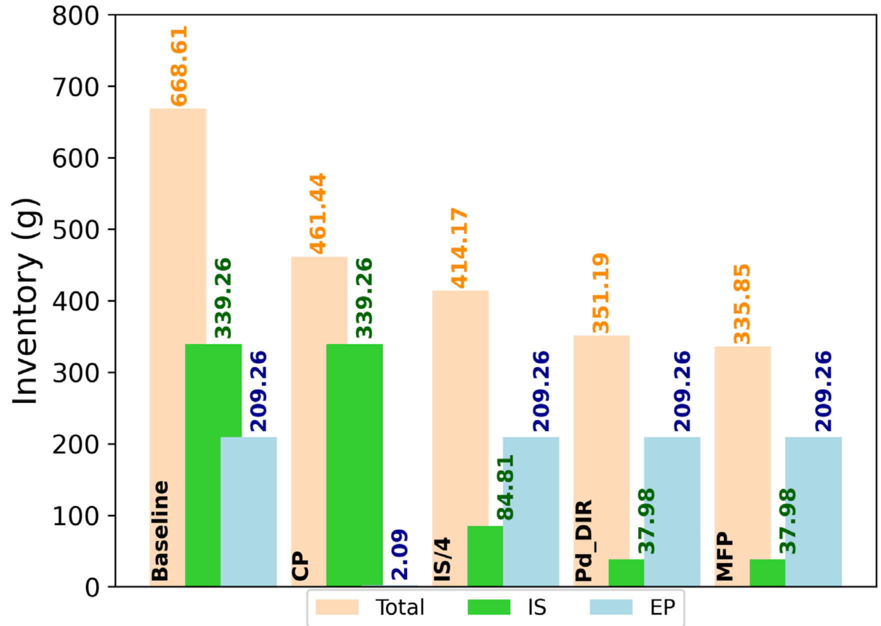

Figure 6. Calculated IPI after 365 days for the Total IPI and the IS and EP sub-systems after implementing one of the four in-process inventory reduction methods. The MFP demonstrates the highest potential for improvement, followed closely by Pd diffusers.

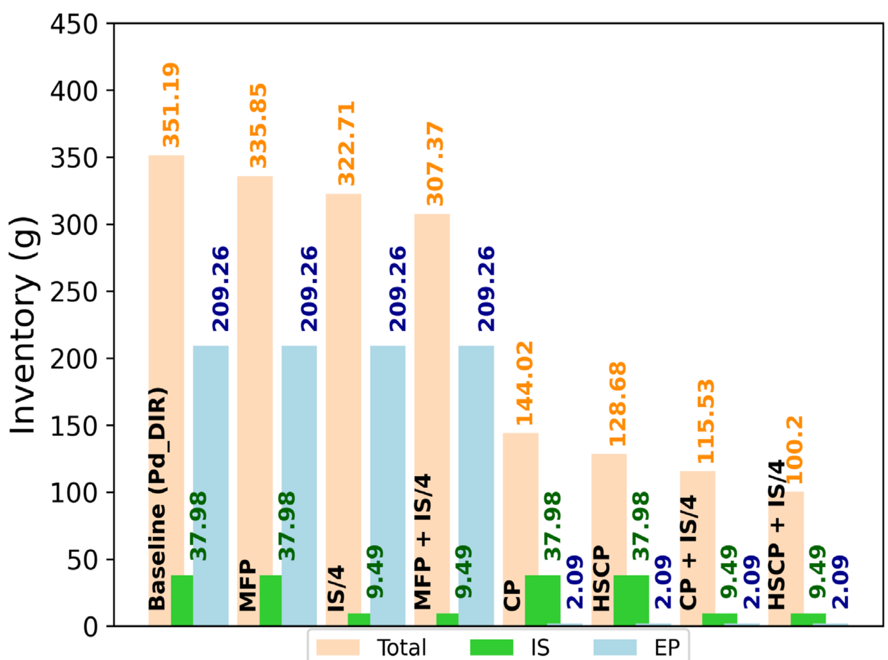

Figure 7. Calculated inventory after 365 days for the Fl, IS, and EP sub-systems, after setting the **Pd_DIR** modifier as the new base line and comparing combinations of modifiers.