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Feasibility of Isotopically Tailored Low Activation Materials

Jonah Duran
Brian Egle

June 2025

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Enrichment Science and Engineering Division

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ABSTRACT

Materials employed in future fusion reactors and advanced fission reactors are susceptible to activation and transmutation due to fast neutron flux, which drives the need for low activation materials for survivability, maintenance, and long-term disposal considerations. This paper investigates the feasibility of using the US Department of Energy's Oak Ridge National Laboratory (ORNL) planned enrichment technologies to produce isotopically enriched or depleted materials for use in future reactor construction. Isotopes of interest have been identified and estimates performed on the required scale of enrichment to impact future design and operation efforts.

1. PROBLEM STATEMENT

Future fusion reactors plan to use deuterium and tritium as fuel. Fusion of these two hydrogen isotopes produces 14.1 MeV neutrons that impinge on the walls and surrounding structures, thereby generating neutron-induced radioactivity that negatively impacts the ability to perform maintenance and safely dispose of waste.

By modifying the isotopic composition within reactor materials, the negative impact of activity can be reduced. Elemental substitutions are currently used to produce materials that are resistant to activation. Some examples include reduced activation ferritic-martensitic steels, vanadium alloys, and SiC/SiC composites. The tradeoff of elemental substitution is the loss of advantageous properties that the traditional materials and alloying agents provide. Through isotopic tailoring, the problem isotopes in this application can be specifically depleted to reduce their contribution to induced radioactivity while maintaining the element-specific advantages.

ORNL has a long history of isotope enrichment. Current enrichment capabilities may provide a solution to produce enriched isotopes. However, several solutions for commercial nuclear activation require a high-throughput device for enriched isotope production. A Plasma Separation Process (PSP) device could meet the need for producing such enriched and depleted materials [1].

2. BACKGROUND

Enriched stable isotopes have proven beneficial for medical applications, environmental safety, national security, nuclear science, and as an efficient fuel in nuclear reactors. The use of enriched material in nuclear reactors is specifically of interest because it provides a method for producing materials with a low activation profile for short-, medium-, and long-lived nuclides. Although the inclusion of these materials requires increased initial capital investment, there are financial and safety incentives to incorporating isotopically tailored materials in the next generation of reactors. These incentives are quoted below from Seki (1998) and Morgan (2015) [2, 3].

Financial-based incentives include:

- reducing the cooldown period required for maintenance, thus increasing plant availability;
- reducing the shielding required within the fusion vessel and within waste processing plants;
- reducing the amount of and classification of radioactive waste that would need to be sent for land burial;
- increased availability of materials with more longevity;
- reducing the cost of replacing components; and
- increased thermodynamic efficiency.

Safety-based incentives include:

- reduced radioactive impact to the environment during normal and accident scenarios;
- reduction of decay heat during loss of coolant accident; and
- reduced gamma-ray dose during maintenance.

Many of these incentives may be realized through the isotopic tailoring of materials and alloy systems used in future nuclear environments. The Code of Federal Regulations (10 CFR Part 61) on licensing requirements for land disposal of radioactive waste identifies several classifications of radioactive waste that may apply to future fusion power plants [4]. It is attractive for such nuclear reactors to have components that comply with these regulations such that generated waste may be stored in a local shallow burial site as low-level waste (LLW). It is therefore desirable to avoid the generation of high-level waste (HLW) that requires long-term storage in a geologic repository. 10 CFR Part 61, as well as the Nuclear Safety Commission, have identified key radionuclides that are regulated and used to determine the classification of waste products [2]. The parents of these nuclides are of key interest for isotopic tailoring such that the products are reduced. These will be considered along with additional elements and alloys of interest to the field, including zirconium (Zr)-based zircaloys, stainless steels, molybdenum (Mo) alloys such as TZM, nickel (Ni)-based Inconels, and more [5].

3. ELEMENTS AND APPLICATIONS

Nuclear systems require advanced materials that utilize a broad range of elements. Section 3 investigates several elements and alloys of interest and discusses their applications in both nuclear fission and fusion environments. Nuclear data for a fusion neutron spectrum are not as readily available in comparison to thermal neutron data for fission. Cross sections for thermal neutron interactions are listed but fusion neutron reactions should be further investigated to support this work.

Nuclear fusion has several plasma confinement concepts that are not considered here. Tokamaks, as the front runner for magnetically confined fusion systems, are the systems used to discuss the mass of isotopes required for low activation materials herein. Tokamak designs are highly variable in size, so material requirements are variable and based on a given plasma volume or confinement device design. Compact fusion devices are highly attractive considering their smaller size. These designs are enabled by recent advancements in magnet technology. With smaller size comes decreased material costs involved in the construction of the tokamak's structural materials. Many of the material mass calculations presented in the following sections are based on the ARC tokamak design presented in Kuang (2018) [6]. The plasma volume for ARC is on the order of 80 m^3 which is comparable to JET, the largest tokamak at the time of this writing. For comparison, several tokamaks and their plasma volumes are listed in Table 1. With an increase in plasma volume comes an increase in the size of the plasma confinement device. This size increase is also tied to the material mass used in construction components such as the inner walls, vacuum vessel, neutron multiplier, coolant, magnet shielding, and more.

Table 1. A comparison of the plasma volumes in ARC, JET, JT-60SA, ITER, and DEMO. This table is adapted from the F4E website [7].

Tokamak	Plasma Volume [m^3]
ARC	80
JET	80
JT-60SA	135
ITER	800
DEMO	1,000–3,500

The level of enrichment required in low activation materials is also an important factor to consider. Many studies assume complete isotopic replacement with one isotope. This assumption is impractical for all currently available enrichment techniques. Acceptable levels of enrichment should be considered in future studies. This topic is closely related to the issue in the lack of available nuclear data. With proper nuclear transmutation models, the allowed level of impurities can be used to estimate the level of enrichment that is necessary to meet 10 CFR Part 61 and Nuclear Safety Commission requirements for LLW.

3.1 ZIRCONIUM

Zirconium alloys, known as the trademarked *zircaloy*, are routinely used in the nuclear fission industry. Reactor fuel cladding is often Zr alloyed with different materials including strontium (Sn) and iron (Fe) to improve the corrosion resistance of the alloy. Zircaloy claddings are an example of how isotopic tailoring could reduce the activation of the material through the depletion of the Zr-92 isotope from natural Zr [8]. There are five stable isotopes of Zr listed in Table 2.

Table 2. Natural isotopic composition of Zr.

Isotope	Zr-90	Zr-91	Zr-92	Zr-94	Zr-96
Composition	0.5145	0.1122	0.1715	0.1738	0.0280

The Zr-92(n,γ)Zr-93 reaction (~0.2 barns for thermal neutrons at 0.025 eV) produces the long-lived Zr-93 isotope with a half-life of 1.53×10^6 years. The accumulation of this radioisotope during operations requires material to be stored in a long-term geologic repository following decommissioning. Calculations have shown that enrichment of the Zr-90 isotope up to 99% has the potential to decrease the radioactivity of decommissioned material to hands-on levels after 5 years of cooling and 3 years of irradiation under a VVER-1000 reactor fission neutron spectrum [9]. This dramatic decrease in radioactivity is ideal for low activation material applications. Recall the high natural abundance of Zr-90 at 51.452% of the total elemental composition; High throughput and enrichment is feasible with existing enrichment technology. The challenge with Zr is revealed in the quantities that are required in existing fission systems. Current nuclear fission reactors use tens of tons of Zr for their zircaloys. Producing this level of inventory poses a unique challenge.

3.2 ZINC

Zinc (Zn) is used in the nuclear fission industry as a corrosion inhibitor. This material is added to water after being depleted of Zn-64 to less than 1% of the isotopic composition. Less activation products form with this depleted material thus lowering worker exposure during maintenance periods. Natural Zn is comprised of the five isotopes listed in Table 3.

Table 3. Natural isotopic composition of Zn.

Isotope	Zn-64	Zn-66	Zn-67	Zn-68	Zn-70
Composition	0.4917	0.2773	0.0404	0.1845	0.0061

Natural Zn is highly abundant in Zn-64, which produces Zn-65 via the ^{64}Zn (n,γ) ^{65}Zn reaction (0.76 barns for thermal neutrons). The Zn-65 then decays via electron capture and β^+ emission as well as to an excited state of Cu-65 which emits gamma radiation. To avoid these issues, hundreds of kilograms of Depleted Zinc Oxide (DZO) are required on an annual basis by the U.S. nuclear power industry.

3.3 GADOLINIUM

While not a low activation material, fission utilizes gadolinium (Gd) as a burnable poison for reactivity control. The Gd assists in regulating the fission rate and maintaining stability by absorbing excess neutrons. Natural Gd is used in the current reactor fleet and is comprised of seven natural isotopes including those listed in Table 4.

Table 4. Natural isotopic composition of Gd.

Isotope	Gd-152	Gd-154	Gd-155	Gd-156	Gd-157	Gd-158	Gd-160
Composition	0.0020	0.0218	0.1480	0.2047	0.1565	0.2484	0.2186

Natural Gd has a weight averaged neutron capture cross section for thermal neutrons of approximately 49,000 barns. Enriched Gd-157 (255,000 barns) up to 70% has been shown to have economic benefits through potential fuel cost savings of up to $60 million per year for the US nuclear power fleet [10, 11]. The relatively high natural abundance of Gd-157 at 15.6518 % makes the production of enriched Gd-157 more feasible than less abundant isotopes like Gd-152 at merely 0.2029% of the natural material. Each boiling water reactor plant is capable of consuming ~38 kg of enriched Gd metal per year. For the entire US fleet of 32 reactors, this would require ~1,300 kg of 70% Gd-157 metal production per year.

3.4 NICKEL

A recurring element in many alloys of interest to the nuclear fusion community is Ni. This material is used in several structural material alloys and has high corrosion resistance for molten salts including FLiBe [12, 13]. Natural Ni has five isotopes listed in Table 5.

Table 5. Natural isotopic composition of Ni.

Isotope	Ni-58	Ni-60	Ni-61	Ni-62	Ni-64
Composition	0.68077	0.26223	0.011399	0.036346	0.009255

The activation issue with Ni is most prevalent in nuclear systems for medium- to long-term storage and is driven mostly by Ni-58 and Ni-62 because of the rather high affinity for neutron capture of both isotopes, thereby leading to the production of Ni-59 and Ni-63. When used in large quantities, isotopic depletion of Ni-62 would greatly reduce the negative impact of activation in Ni and Ni-based alloys by reducing the amount of Ni-63 (half-life of ~100 years). Depletion of Ni-58 reduction would reduce the production of Ni-59 (half-life of ~80,000 years) [14]. In an ideal scenario, depletion of these two isotopes with additional enrichment of Ni-61 may be used to substitute natural material utilizing Ni, thereby eliminating the induced radioactivity from (n,2n) and (n,γ) reactions of Ni-59 and Ni-63.

Inconel is a common material used in the production of current nuclear fission facilities and is comprised of ~70% Ni, depending on the variant. The issue with replacing all Inconel with isotopically modified Ni is akin to Zr in that the sheer quantities required for industrial-scale nuclear systems are immense. Although the need and benefits are clear, the production rates for industrial-scale inventory requirements may be prohibitive.

Another use for Ni that is more feasible for planned production technology is corrosion barriers for molten salt fusion blankets that are currently being considered in future fusion reactors. A thin coating on the surface of the components that interact with the molten salt on the order of hundreds of microns thick could be feasible for production with planned enrichment technology. Commonwealth Fusion Systems (CFS) is a startup company developing an affordable, robust, and compact (i.e., ARC) fusion system [15]. CFS plans, with ARC, to utilize a molten salt blanket for heat conversion, fuel production, magnet shielding, and blanket coolant. The leading molten salt for the fusion blanket is FLiBe. An example of this blanket is shown in Figure 1 of Forsberg (2020) [16]. To estimate the amount of Ni required to coat these systems, the size of the salt wetted area of the immersion tanks and coolant channels needs to be estimated. The main chamber vacuum vessel of ARC has a wall area of ~200 m^2 and is comparable in size to the surrounding cooling channel [6]. Assuming this area will be coated in 100 µm of Ni, 0.02 m^3 of Ni is required. As far as density, Ni has a density of 8.9 g/cm^3 or 8900 kg/m^3; therefore, 178 kg of isotopically tailored Ni is required to coat an area equivalent to the size of ARC's vacuum vessel.

Additionally, Ni is being considered for use in tungsten heavy alloys (WHA) as a component of the plasma facing materials which directly interact with the fusion plasma [17]. These alloys contain up to 97% W with an admixture of Ni and Fe that makes up the remainder of the compound. Compared to bulk W, these WHAs are cheaper and easily machinable. They also have the attractive properties of decreased brittle behavior vs. pure W tiles while retaining a low sputter rate and high service temperature. This improvement could be combined with the additional benefits of isotopically tailoring the Ni with depleted Ni-58 and Ni-62 for improved activation properties. ARC has also considered the use of a 1 mm thick W first wall that is supported by a 1 cm Inconel inner vacuum vessel structural material [6]. Assuming a 200 m^2 wall area and 3 wt % Ni in a WHA being used in the 1 mm thick first wall, approximately 53.4 kg of isotopically tailored Ni is required.

3.5 TUNGSTEN

Considering the extreme temperature requirements of the materials used to face the confined plasma, W is a highly attractive material for fusion environments. Other than carbon (C), W has the highest melting temperature of the elements at 3,422°C. There are five natural isotopes of W listed in Table 6.

Table 6. Natural isotopic composition of W.

Isotope	W-180	W-182	W-183	W-184	W-186
Composition	0.0012	0.2650	0.1431	0.3064	0.2843

Tungsten is currently used as a replacement for Mo and Ni in several low activation alloys for future fusion systems. However, this elemental replacement results in the production of undesirable daughter products, as well as a loss of favorable material properties that may lead to increased fusion power plant availability, thermodynamic efficiency, and net power provided through material property improvements. Isotopic tailoring of the material could be beneficial for thermal armor and applications including WHAs, as is mentioned in the previous section on Ni applications.

Considering a 1 mm thick wall with ~200 m^2 of plasma wetted area, and following the calculations performed in Section 3.4, ~3,700 kg of enriched isotopic W material is required for an isotopically tailored WHA layer. Enrichment of W-184 is most beneficial for isotopic tailoring in order to reduce the cooling time of components required by recycling limits [18]. However, isotopic depletion of W-186 is attractive for mitigating production of undesirable transmutation products including rhenium (Re) and osmium (Os) [19]. Both products have undesirable mechanical properties and activation characteristics.

3.6 MOLYBDENUM

Molybdenum is an attractive element to the fusion community in regions of high neutron flux and thermal loads. It has similar uses to that of W but exposure of Mo to the intense neutron flux that is expected in fusion environments can generate significant radioactivity issues [20]. The element is comprised of seven natural isotopes listed in Table 7.

Table 7. Natural isotopic composition of Mo.

Isotope	Mo-92	Mo-94	Mo-95	Mo-96	Mo-97	Mo-98	Mo-100
Composition	0.1453	0.0915	0.1584	0.1667	0.0960	0.2439	0.0982

Natural Mo generates several radionuclides, including the most dominant Tc-99m, Mo-99, Nb-91m, Nb-93m, Nb-91, Mo-93, Nb-94, and Tc-99. These problem radionuclides come predominantly from Mo-92 and Mo-94, and none of these are generated from Mo-96 or Mo-97.

Molybdenum could be implemented in the blanket and wall materials of a fusion device using 65,000 kg of total material. This would be needed to replace 120,000 kg of W that is planned for the DEMO device as the leading candidate material. These quantities are low in comparison to the 4,500,000 kg of in-vessel EUROFER steel and more than 20,000,000 kg of Type 316 stainless steel used to create the vacuum vessel. If used strictly in the most demanding divertor environments where the benefits are the greatest, then 9,000 kg of Mo would be sufficient for a 5 mm thick layer of the divertor in a DEMO-sized device [21-23].

It is important to emphasize the difference in scale between the DEMO device mentioned here and the ARC device described in previous sections. The DEMO device is expected to have a plasma volume on the order of ~2,250 m^3 (1,000–3,500 m^3). The ARC device is comparatively compact with a plasma volume that is similar to the JET fusion device, or ~80 m^3 [24, 25]. Considering the material is agnostic of the device and future fusion systems will all face similar activation issues, much less Mo would be needed for an ARC-sized system that approaches hundreds of kilograms, rather than thousands of kilograms for a DEMO-sized system.

Another common use for Mo is as an alloying agent in stainless steels. One study has shown that the combined tailoring of Ni-61 and Mo-97 in Type 316 stainless steels with enrichment levels of 99% result in a decrease in the radioactivity at 50 years after shutdown by a factor of 100 over natural Ni and Mo alloys [5]. This favorable trend continues with increased enrichment. These two materials alone are shown to dramatically alter the activation of the materials. The ideal recipe for isotopically tailored Type 316 stainless steel would include the enrichment of Ni-61, Mo-96, Mo-97, and Cr-53 up to at least 99.95%. Additionally, the isotopes of Fe may be depleted such that Fe-54 is removed from the steel. This ideal recipe shows that enrichment technology should be flexible enough to allow for select enrichment or depletion of the isotopes of interest.

3.7 TITANIUM

Titanium (Ti) is a common constituent of various alloys that are considered for fusion materials [18, 26-29]. Vanadium alloys, such as V-15Cr-5Ti, are attractive low activation alternatives for structural materials and ceramic coatings in regions of intense neutron flux [26]. The Ti has added benefits in that it has been shown to substantially improve the radiation-induced swelling characteristics of the material and fabricability when over 1% of the alloy is comprised of Ti [30]. Natural Ti is comprised of five isotopes listed in Table 8.

Table 8. Natural isotopic composition of Ti.

Isotope	Ti-46	Ti-47	Ti-48	Ti-49	Ti-50
Composition	0.0825	0.0744	0.7372	0.0541	0.0518

Scandium (Sc), calcium (Ca), potassium (K), and argon (Ar) radioisotopes are transmuted products of Ti in fusion environments. The Ti-50 isotope produces the least of these transmuted products and is the most attractive for enrichment and reduction of activation [29]. Vanadium alloys and thin films are the most economically feasible applications for enriched Ti isotopes. The inner vacuum vessel for ARC could take advantage of the V-15Cr-5Ti alloy. According to Kuang (2018), the inner vacuum vessel has a volume of 3.5 m^3. This volume would require ~1,081 kg of enriched Ti to construct. The outer vacuum vessel has a volume of 10.7 m^3, thus requiring ~3,305 kg of enriched Ti. Thin films and coating applications would require significantly less material, as noted in the Ni section calculations.

3.8 BORON

There are NbTi-based superconducting magnets being used in current fusion devices. Boron (B) inclusive MgB_2 magnets could provide a low activation alternative that has the additional benefit of higher operating temperatures over other conventional superconductors. Additional isotopic tailoring of B-11 has been shown to provide additional benefits [31-33]. Natural B is comprised of the two isotopes listed in Table 9.

Table 9. Natural isotopic composition of B.

Isotope	B-10	B-11
Composition	0.199	0.801

The B-10 isotope has a high cross section neutron reaction that forms Li-7 and He; however, B-11 is neutron resilient and has no (n, α) reaction, making it a low activation alternative when isotopically tailoring the superconductor to $Mg^{11}B_2$. These enriched materials are most applicable to low-field magnet applications for fusion systems. Poloidal field and correction coils are both areas where NbTi could be replaced. In an ITER-sized tokamak (800 m^3), approximately 250,000 kg of enriched B-11 are estimated to be required for use in constructing the poloidal field coils [34]. These large quantities, coupled with magnet advancements such as ReBCO (i.e., rare-earth barium copper oxide) high temperature superconducting tape, may make MgB_2 a less attractive alternative material.

Diboride ceramics, such as TiB_2 and ZrB_2, are attractive alternatives under consideration for plasma facing materials. However, these ceramics would need to be comprised of B-11 to avoid the irradiation instabilities from B-10 He production.

3.9 LITHIUM

Enriched isotopes of lithium (Li) are attractive to both fusion and fission industries, and there are two isotopes of lithium as shown in Table 10.

Table 10. Natural isotopic composition of Li.

Isotope	Li-6	Li-7
Composition	0.0759	0.9241

Section 3.4 alluded to the use of FLiBe salts as blanket coolant in future fusion power plants. These coolant channels may also be used as breeding blankets for tritium fuel production. The Li within the FLiBe should be enriched with Li-6 due to the large cross section for the following reaction [35].

$$n + {}^{6}Li \rightarrow T + \alpha + 4.8\ MeV$$

The above reaction is neutron efficient and helps to increase the tritium breeding ratio (TBR) to acceptable levels. The TBR is highly dependent on the system but the lack of a viable supply route threatens the success of future nuclear fusion power plants. Fission systems use enriched Li-7 as a corrosion inhibitor in power reactors. Current Li supply is largely dependent on foreign entities, including Russia and China. For current fission system needs, nearly 500 kg of enriched Li-7 is imported to the United States on an annual basis. Future fusion power systems will require significant quantities of enriched Li-6. The level of enrichment can be as low as 10% but is heavily dependent on the breeding concept [36]. In terms of the quantity of enriched Li-6, Giegerich (2019) suggests 100 kg of material will be consumed annually [37].

3.10 SILICON

Several studies have shown SiC as a promising low activation structural material for future fusion devices [38]. The use of impurity-free SiC could permit full-contact hands-on maintenance, which would meet the criteria for unrestricted waste. Although impurity free is unlikely, a high purity of <10 appm total Fe, Ni, Cu, and Mo would result in limited-contact Class A waste that would grant maintenance personnel access to the outside of the blanket for limited maintenance. Additional benefits from isotopically tailored Si are possible. Natural Si is comprised of Si-28, Si-29, and Si-30, with abundance values shown in Table 11.

Table 11. Natural isotopic composition of Si.

Isotope	Si-28	Si-29	Si-30
Composition	0.92223	0.04685	0.03092

Notably, Al-26, with a half-life of $\tau_{1/2} = 7.2 \times 10^5$ years, is one activation product generated by Si-28 that negatively affects the long-term dose rates of the material. Isotopic depletion of Si-28 would eliminate this reaction and leave a 60–40 mixture of Si-29 and Si-30 for use in the production of SiC [39]. One study identified uses for SiC in the limiter, first wall, blanket, shielding, and toroidal field coils of a fusion device that resulted in a material mass requirement in the range of megatons. This high mass requirement along with the impurity requirement of the material requires unique enrichment solutions.

4. SOLUTION

The DOE Isotope Program (DOE IP) considers developing modern enrichment technology for stable isotopes a primary research area of interest. DOE IP supports world-leading research and development associated with creating novel and more efficient isotope production and processing techniques and has been at the forefront of development and production of radioactive and stable isotopes that are used worldwide. As such, DOE IP is currently working with advanced nuclear fission and fusion energy companies to establish the enriched stable isotope supply chains necessary for development, demonstration, and deployment projects.

There are a variety of methods and techniques that can provide the capability to enrich isotopes of a given element [40]. These methods take advantage of different elemental properties including isotope mass, chemical reaction rates, and nuclear resonance. These different methods are often limited to specific feedstock forms and provide low throughput of enriched materials. For the quantities of material that have been discussed for low activation materials, a high-throughput method of enrichment is necessary to provide industrial quantities of isotopically tailored materials. PSP is one isotope enrichment technique that may fill this need.

The PSP technique is based on ion cyclotron resonance heating (ICRH) that is commonly used in nuclear fusion systems for plasma heating. ICRH was recognized as a viable method for selective isotope separation in the 1970’s, as described in the experimental work of John Dawson [41]. Since this discovery, the United States, France, and Russia have developed the PSP technique and proven its capability with separate isotopes across a wide mass range, as shown in Table 12 [1, 10, 11, 40-50].

Table 12. Isotopes modeled and processed with PSP at various facilities.

Device	Method	Isotopes
Theragenics [1]	Processed	Ni-60, Ni-62, Zn-70, Mo-92, Mo-98, Mo-100, Pd-102, Gd-157, Gd-160, Dy-164, Er-167, Er-170
Theragenics [1]	Modeled	Ti-48, Fe-57, Cu-63, Ge-72, Ge-76, Rb-87, In-113, Cd-114, Nd-146, Nd-148, Nd-150, Gd-152, Yb-176, Lu-176, Hf-178, Ir-191, Th-203
ERIC [46]	Processed	Ca-43, Ca-44, Ca-48, Zn-64, Zn-68, Cd-110, Ba-132, Yb-176, Cr-50, Ni-62, Pd-102
SIRENA [48]	Processed	Li-6
KEK Test Machine [49]	Modeled	Mo-98, Mo-100
Nonlinear-Ion-Dynamics-LLC Prototype [50]	Processed	Rb-85, Rb-87

PSP is described as a separation technique capable of enriching isotopes between masses 40 and 208. However, some devices have shown unique designs capable of separating low mass isotopes such as Li [48]. Historically, the source material for PSP is restricted based on two material characteristics: the element of interest must be introduced in a solid state at room temperature, and it must be considered a conducting material [48]. However, there are unique source designs which have expanded the realm of possibility for feedstock introduction and material. The mass range and historical material considerations are especially attractive because they include the rare-earth elements which are usually incompatible with other separation techniques.

PSP has been modeled and developed to process materials at a variety of facilities listed in Table 12. The PSP facilities were successful in enriching isotopes to the range of ~70–90% with a high throughput of material on the order of grams and kilograms per year. Some models have shown device capabilities as high as 99% enrichment and hundreds of kilograms per year. These numbers have also been modeled for a modern PSP device. Previous PSP systems generally used superconducting magnets that produced fields of ~2 T. Plasma mass separation is shown to increase with magnetic field. Models of systems with higher magnetic fields can provide high throughput and enrichment factors across a wider mass range than the ~2 T systems.

As shown in Table 12 and as noted in the paper by Bigelow (2005), ORNL has prior experience with PSP through a DOE agreement with the Theragenics corporation [1]. During the development of the PSP device, a wide range of elements were processed using the Theragenics PSP. Additionally, a plan was developed for a next generation PSP facility capable of producing the necessary quantities of enriched materials to benefit the nuclear fusion and fission industries [10]. To progress PSP technology and prepare for a commercial-scale production facility, a PSP test stand was highlighted as a beneficial stepping stone between modern PSP capabilities and the next generation technology that can produce several isotopes for nuclear energy facilities. The next generation facility could also support the ongoing need to replace the diminishing U.S. stable isotope inventory that was produced during the calutron era. Enriched material collected from a PSP capability could also be used as pre-enriched feedstock for other enrichment technologies that are capable of enriching isotopes to levels greater than 99 %.

5. CONCLUSION

Novel materials are required to influence the survivability, maintenance, and long-term disposal considerations for nuclear power facilities. Low activation materials are one solution that is shown to benefit from isotopic replacement of natural elements to minimize the impact of daughter products formed during plant operations.

Low activation materials would greatly benefit from isotopic tailoring, but enriched isotopes have clear benefits within additional aspects of the nuclear industry. Applications include reactor fuel cladding, corrosion inhibitors, burnable poisons, alloying agents, plasma facing components, gas mitigation materials, thermal armors, structural materials, ceramic coatings, magnet materials, breeder blankets, diagnostics, heating systems, and more. The quantity of material required for structural materials poses a unique challenge for all isotopic enrichment techniques; however, the other use cases that require ~1,000 kg/y of enriched isotopic material or less are feasible candidates for production when using an isotope enrichment technique such as PSP.

Although this paper focuses on use cases and material quantities (Table 13), there are several other considerations that are available areas of future research to support this work. For example, the cost of isotopic adjustment must be considered and balanced against the cost of radioactive waste disposal. The framework for this type of study was well described by the Gd enrichment study by Grossbeck (2003) and Egle (2020) [10, 11]. The National Isotope Development Center (NIDC) could also be used to compare isotope production sources, current inventories, and final product costs with the use cases presented here. Transmutation products from material interaction with an expected fusion power plant neutron spectrum should also be considered in evaluating the level of isotopic enrichment that is necessary for the materials in Section 3. Many studies consider impurities that are present in currently available industrial materials. As with other isotope separation techniques, including PSP, many of those impurities are filtered out through enrichment of a single isotope. Therefore, PSP has the additional benefit of removing non-resonant ions from the plasma for increased isotopic and elemental purity.

Table 13. Isotopes of interest and necessary quantities for production. Items listed by production quantity.

Element	Isotopes for Enrichment	Isotopes for Depletion	Quantity
Nickel	-	Ni-58, Ni-62	~50–200 kg
Zinc	-	Zn-65	100’s of kgs
Molybdenum	Mo-96, Mo-97	Mo-92, Mo-94	100’s of kgs
Lithium	Li-6, Li-7	-	100’s of kgs
Titanium	Ti-50	-	~1,000 kg
Gadolinium	Gd-157	-	~1,300 kg
Tungsten	W-184	W-186	~3,700 kg
Zirconium	Zr-90	Zr-92	1,000’s of kgs
Boron	B-11	B-10	1,000’s of kgs
Silicon	-	Si-28	1,000’s of kgs

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