applied sciences

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Potential of Radioactive Isotopes Production in DEMO for Commercial Use

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Abstract: There is widespread use of nuclear radiation for medical imagery and treatments. Worldwide, almost 40 million treatments are performed per year. There are also applications of radiation sources in other commercial fields, e.g., for weld inspection or steelmaking processes, in consumer products, in the food industry, and in agriculture. The large number of neutrons generated in a fusion reactor such as DEMO could potentially contribute to the production of the required radioactive isotopes. The associated commercial value of these isotopes could mitigate the capital investments and operating costs of a large fusion plant. The potential of producing various radioactive isotopes was studied from material pieces arranged inside a DEMO equatorial port plug. In this location, they are exposed to an intensive neutron spectrum suitable for a high isotope production rate. For this purpose, the full 3D geometry of one DEMO toroidal sector with an irradiation chamber in the equatorial port plug was modeled with an MCNP code to perform neutron transport simulations. Subsequent activation calculations provide detailed information on the quality and composition of the produced radioactive isotopes. The technical feasibility and the commercial potential of the production of various isotopes in the DEMO port are reported.

Keywords: DEMO; irradiation unit; neutronics; isotopes production

Citation: Pereslavtsev, P.; Bachmann, C.; Elbez-Uzan, J.; Park, J.H. Potential of Radioactive Isotopes Production in DEMO for Commercial Use. *Appl. Sci.* **2024**, *14*, 442. https://doi.org/10.3390/app14010442

Academic Editor: Antonino Pietropaolo

Received: 13 November 2023
Revised: 20 December 2023
Accepted: 26 December 2023
Published: 3 January 2024

1. Introduction

One of the evident issues in the realization of commercial fusion power is to reduce the cost of electricity sufficiently to be competitive with other commercial energy sources. Furthermore, a broad public acceptance of the sophisticated fusion power source is targeted [1]. The DEMO development project is in its second phase, the Concept design phase, aimed at increasing the maturity of the baseline concept. Within this phase, main systems are planned to be selected and designed [2,3]. As a very innovative option, the intensive volumetric DEMO plasma neutron source could potentially contribute to the production of various radioactive isotopes for commercial applications in medicine, in industry, in measuring technologies, and in agriculture. The associated commercial value of these isotopes could mitigate the capital investments and operating costs of such complex fusion plants like DEMO and, therefore, could contribute to the overall public acceptance of the fusion energy source. To this end, an equatorial port could be reserved in the DEMO tokamak with a primary purpose to arrange a facility (irradiation unit) for the routine production of different isotope in an industrial scale.

An additional noble goal of the DEMO as a supplier of the radioactive isotopes for the fight against dangerous human diseases could facilitate the acceptance of the whole project. This paper presents an assessment of the technical feasibility and the commercial potential of the various isotopes' production in the especially dedicated DEMO port. Such a study assumes the use of a procedure with the ultimate goal of developing a suitable geometry

layout of the irradiation unit arranged in the DEMO port to perform numerical simulations and to estimate a possible outcome of the isotope production as well as a potential financial yield. The scheme used in this work assumes several steps of the new elaborations and investigations, resulting in solid geometry models that serve as a basis for an achievement of credible results of the particle transport calculations. The adopted procedure includes the following steps: an elaboration of the CAD-based geometry model of the DEMO reactor with the irradiation port, conversion of this model into an MCNP model, a production of the MCNP input file with the integrated irradiation unit, MCNP simulations, consequent activation calculations, and analysis of the results.

2. Survey of Commercial Use of Radioactive Isotopes

2.1. Radioisotopes Used in Medical Applications

There is widespread utilization of gamma and beta irradiation and radioactive radionuclides in medical applications, especially for diagnosis (recognition) and healing (treatment) of diverse human situations. Medicine applies nuclear radiation to give rationality about the status of different organs in a human body or to treat such severe disease as cancer. Almost 40 million medical treatments worldwide are carried out yearly, with a strong increasing tendency up to 5% per year [4]. The nuclear radiation provided by industrial radioactive isotopes is also used for the purpose of medical equipment sterilization.

There are numerous radioactive isotopes with a large variety of applications in medicine. These include both short- and long-lived nuclides such as ^{213}Bi ($T_{1/2}$ = 43 min) and ^{60}Co ($T_{1/2}$ = 5.27 years), respectively.

An intensively growing nuclear medicine operates with diverse sources of nuclear radiation to make possible a justified diagnosis of diseased, affected human organs and to assign proper treatment in the case of serious sicknesses such as cancer. This opens a unique opportunity to obtain a picture of the human body in vitro and enables a quick diagnosis. All imaging devices are driven by decaying radioisotopes. A dose of the specific radioactivity can be delivered to the human body and the special distribution of the activity absorbed in various locations can be analyzed, making use of 2D or 3D pictures. Such radioactive tracers emitting gamma rays are usually short-lived isotopes, for instance, ^{99m}Tc and ^{131}I, which can be given by injection or orally. A computer tomography (CT) intensively used worldwide utilizes a gamma radiation source loaded with short-lived isotopes like ^{169}Yb or ^{192}Ir. Every organ in the human body acts differently and absorbs mainly specific chemicals. This feature is routinely used in medicine to assign different isotopes of chemical elements for the customized imaging of different organs. For the purposes of a reliable diagnosis, the radioisotopes should have high enough gamma energy that allows them to avoid absorption in the human body and to leave it for further detection. They also must have a relatively short half-life to disappear from the body due to the radioactive decay shortly after screening is finished. In the case of ^{99m}Tc radioactive decay, the ^{99}Mo isotope is produced, which is used in almost 80% of the medical treatments over the world [4].

The radioactive isotopes are also used to expose affected human organs, with the goal of controlling or eliminating growing tumor cells (so-called gamma knife radiosurgery). The external source of the gamma irradiation, for example, decaying ^{60}Co, can be used for the focused exposure of a precise area in the human body. Internal radiotherapy allows locally concentrated radiation by the placing of a compact radioactive source of gamma or better radiation in a specific area in the human body (brachytherapy), and this is becoming the most important and successful tumor treatment. Implant seeds containing ^{131}I, ^{192}Ir can be used for short (up to 15 min) in vitro irradiations and ^{125}I, ^{103}Pd implants can be used for the permanent treatments of the patients. The ^{177}Lu isotope with the low-energy beta emission helps in some cases where other treatments fail. Radioactive isotopes ^{153}Sm or ^{186}Re are also used with significant success in palliative procedures to relieve pain [4]. Treatments aiming at destroying malfunctioning cells by means of beta radiation (radiotherapy) use ^{177}Lu and ^{90}Y [4].

Another industrial-scale field for radioisotope applications is the sterilization of the medical tools as well as heat-sensible products, for instance, solutions and powders for patient treatments. Such processing of the medical materials, called cool processing, is the preferred method to sterilize biological materials to be utilized in grafting, for example, of skin, nerve, or bones. This technology is used to sterilize almost half of the single-used medical items: surgical gloves, heart valves, plastic pieces, etc. The ^{60}Co isotope is used for these purposes and can be seen as the main "working horse" actively used worldwide. Such equipment for a large-scale gamma exposure and processing are in industrial use in many countries.

2.2. Radioisotopes Used in Other Fields

Worldwide, up to 30% of the food harvest is commonly lost due to pollution before consumption. In order to kill bacteria, food products are subjected to gamma irradiation, enabling preservation to increase a shelf life and to control pests. Several radioisotopes (for example, ^{204}Tl) are used in the industry to monitor fluid flows, detect leakage, ensure integrity of welds in pipe systems, and also to measure steel sheet thickness, etc.

2.3. Radioisotopes for Potential Production in DEMO

The two main sources of the radioactive isotopes are nuclear reactors and accelerators. The majority of them are produced in fission reactors, with the possibility to generate a big number of different isotopes and with a flexible exposure time from hours to years. The accelerators are usually used to produce isotopes with unique properties or to replace reactors to reduce a proliferation risk due to the utilization of uranium with low or high enrichment. For the production of some radioactive isotopes, the accelerator can be more preferable because of lower, or at least comparable, costs compared to conventional reactors.

The radioisotopes listed below are produced through neutron irradiation of target materials that could potentially be integrated in a port plug of DEMO. These isotopes are, therefore, candidates for production in DEMO.

^{99}Mo

The ^{99m}Tc ($T_{1/2}$ = 6.01 h) isotope was discovered in 1938 from the radioactive decay of ^{99}Mo ($T_{1/2}$ = 65.94 h), and now it is the most widely used isotope tracer for SPECT (single-photon emission computed tomography) imaging. The world's capacity of such procedures is estimated to be ~40 million screenings annually, which is roughly 80% of all treatments involving nuclear radiation [5]. The ^{99}Mo market is assessed to be as big as USD 5 billion yearly, with a forecasted increase of ~9% per year. Over the decades, there have been significant investments in the ^{99}Mo production, and the need for additional ^{99}Mo capacity grows continually. A so-called six-day activity is a special unit applied for the ^{99}Mo production that usually means the activity after 6 days of the processing time. The present ^{99}Mo world demand of about 18,500 six-day TBq/year [5] is covered mainly by six reactors: HFR (Petten, The Netherlands) ~40%, BR-2 (Mol, Belgum) ~20%, Safary-1 in South Africa ~15%, the Australian Opal ~15%, Maria (Świerk, Poland) ~5%, and the reactor LWR-15 in the Czech Republic ~5%. There is an assessment of the ^{99}Mo market size: the Opal annual production (15% of the market) is around 81.4 six-day TBq/week (2200 six-day Ci/week). Due to natural decay of ^{99}Mo during shipping, storage, and processing, the world's supply capability should, and does, significantly exceed the market consumption by up to 50% [5].

The ^{99}Mo can be generated by an exposure to neutron irradiation of either natural molybdenum, metal, and MoO_3, or of the enriched ^{98}Mo through the ^{98}Mo(n,γ)^{99}Mo reaction. The generated specific activity is usually lower compared to the ^{99}Mo produced in research reactors utilizing targets filled with enriched uranium. The typical yield (a reference value used for the comparison in this work) of ^{99}Mo at the end of 1 week of irradiation is ~1.2×10^{10} Bq/g [6,7]. In the case of the production in fission reactors, the activity of the ^{99}Mo is ~4.0×10^{14} Bq/g [7] at the end of ~200 h of irradiation. The cost for the ^{99}Mo production in early 2008 varied from USD 3380 to 8780/TBq (USD 125 to

325/Ci) [8]. The estimated present market value of ^{99}Mo could be USD 6760–17,570/TBq (USD 250–650/Ci).

^{192}Ir

Iridium radioactive sources ($T_{1/2}$ = 73.83 days) are usually delivered in the form of thin wires or thin foil discs. The specific activity of the ^{192}Ir enables the preparation of very small, miniaturized radioactive sources for their utilization in vitro in the human body. Such implants typically require an exchange several times per year [9]. Because of the strong beta emission, this procedure, brachytherapy, is very effective at providing intensive local irradiation, for example, in the head and breast. ^{192}Ir also has applications in industrial radiography to check pipeline welds and to assess the structure of steels and various alloys.

^{192}Ir sources are typically produced by the neutron irradiation exposure of natural iridium through the ^{191}Ir(n,γ)^{192}Ir reaction. The target material, 10 mg of Na_2IrCl_6, is sealed in aluminum capsules of 22 mm diameter and 44–50 mm length for 1 week [6,10]. The typical yield of the ^{192}Ir after irradiation is approximately 68 GBq/g [6]. The total annual world demand exceeds 30,000 Ci (measured at the end of the irradiation). The price for ^{192}Ir radioactive sources varies significantly in the range USD 12,160–27,000/TBq (USD 450–1000/Ci) [11,12].

^{103}Pd

^{103}Pd ($T_{1/2}$ = 16.99 days) radioactive sources supplied to the end medical treatments are enclosed in microseeds with low energy gamma emission that is rapidly absorbed in tissue, for instance, in ophthalmic plaque radiotherapy [13]. The implant with activity of 200–300 μCi [14] is typically positioned in the human body for 2–5 days. This isotope is usually produced through the ^{102}Pd(n,γ)^{103}Pd reaction in aluminum containers of 22 mm diameter and 46–50 mm length irradiated for 1–4 weeks. The typical yield of ^{103}Pd is ~370 MBq per 100 mg of palladium [6]. The cost assessment of ^{103}Pd radioactive sources is complex because the medical treatments with this isotope are on a rising trend. A rough estimate of the commercial price could be USD 6000–12,500/seed [15].

^{169}Yb

^{169}Yb ($T_{1/2}$ = 32.026 days) is a middle-energy brachytherapy decay gamma source; therefore, it is a very promising isotope to provide much higher absorbed dose in human organs compared to ^{192}Ir [16,17]. This isotope is applied for cerebrospinal fluid treatments in the brain [4]. The ^{169}Yb radioactive source is produced in the ^{168}Yb(n,γ)^{169}Yb reaction with the irradiation of ytterbium oxide (Yb_2O_3) for 1 week. To increase the end yield of this isotope, the ^{168}Yb concentration in yttrium is enriched from the natural abundance of 0.13% up to 17.1% [6]. The irradiation of the target material of some 1.14 mg is carried out in a quartz vial of 14 mm diameter and 50 mm height for 1 week. The reference industrial product intensity achieved in such exposure is 1.6 TBq/g [6]. The high specific activity of the ^{169}Yb pieces enables the development of a much more efficient radioactive source as compared to ones loaded with an ^{192}Ir source. The cost of Yb_2O_3 (82% ^{168}Yb) is currently USD ~700/mg and the price of a ~0.37 TBq (10 Ci) ^{169}Yb source is USD 1650–6000 [16].

^{125}I

The industrial production and utilization of ^{125}I ($T_{1/2}$ = 59.408 days) has many applications that become routine. ^{125}I is generated through the neutron irradiation of ^{124}Xe, formation of ^{125}Xe in the ^{124}Xe(n,γ)^{125}Xe reaction, and consequent decay of ^{125}Xe ($T_{1/2}$ = 16.9 h) into ^{125}I. For decades, the seeds for implantation filled with ^{125}I have been applied in nuclear radiation therapy, called brachytherapy, to treat in vitro malicious tumors. In such treatments, the distance between the seed and specific tumor location is usually short and enables exposure up to a preassigned dose that reduces unnecessary radiation damage of tissue in the vicinity. This isotope is also widely used in radioimmunoassays to detect hormones in tiny quantities [4]. The aluminum target capsule of 27 mm diameter and

200 mm length is filled with 0.4 g of the enriched ^{124}Xe and plugged [6]. The irradiation of the target for up to 1 week is applied to reach the reference specific activity of 6×10^{14} Bq/g. The market price of the ^{125}I sources can differ strongly depending on the specific activity and the volume of the source: USD 0.81–3.2/MBq (USD 30/mCi–USD 120/mCi) both for medical treatments and for industrial applications [18–20]. The world demand of ^{125}I is as high as 37 TBq/year (1000 Ci/year) [10].

^{131}I

This radioisotope is widely used in the treatment and in the imaging of thyroid cancer. Very likely, the gamma exposure with this isotope is the most successful treatment of this type of cancer. Because of the strong beta emission, it is also used for beta therapy [4]. The typical production method utilizes the neutron irradiation of ^{130}Te, a consequent decay of a produced isotope into the required radionuclide: ^{130}Te(n,γ)^{131}Te ($T_{1/2}$ = 25 min) $\rightarrow$ ^{131}I ($T_{1/2}$ = 8.04 days). The aluminum capsule of 22 mm diameter and 44–50 mm length is filled with of approximately 20 g of TeO_2 (natural tellurium) and irradiated for 1–4 weeks [6]. Depending on the irradiation facility, the layout of the target, and the irradiation scenario, the specific activity of the product can vary. The reference target activity of the ^{131}I production is of some 1×10^{10} Bq/g [6,10]. The market price strongly depends on the activity requested and it could be in the range of USD 37,840–189,190/TBq (USD 1400–7000/Ci) [21]. We estimate the total annual world demand of ^{131}I to be ~555 TBq (15,000 Ci) assessed by the end of the irradiation [10].

^{60}Co

^{60}Co ($T_{1/2}$ = 5.2714 years) is used for the treatment of brain cancer but mostly for sterilizing of health care items as well as of blood. In the case of a high specific activity and, therefore, smaller sample size, this isotope can be used in radioactive sources replacing ^{192}Ir [9], for example, in gamma knife [22]. The ^{60}Co target is prepared in the form of metallic cylinders of 6.2 mm diameter and 25.4 mm length or in form of the small pellets of 1 mm diameter and 1 mm length [6,22,23]. The irradiation scheme of its production is based on the neutron irradiation of natural cobalt, ^{59}Co(n,γ)^{60}Co. The irradiation time in a CANDU reactor amounts to 18–36 months. The reference specific activity achieved in the irradiation is 2.2×10^{11} Bq/g [22,24]. The prices for the ^{60}Co radioactive sources from international supplies vary from USD 350 to 400/TBq [25] or USD 13–15/Ci.

^{90}Y

Yttrium-90 ($T_{1/2}$ = 64.1 h) is a β-emitter with the maximum emission energy of 2.282 MeV, which makes it very attractive for therapeutic applications, especially for treatment of liver cancer [4]. This isotope is produced after the decay of ^{90}Sr fission product in fission reactors and alternatively through neutron irradiation of natural yttrium, through the ^{89}Y(n,γ)^{90}Y reaction [6], for 1 week. The latter option does not require additional purification of the ^{90}Y from ^{90}Sr traces. For human use, the reference specific activity of 1 Ci/g (3.7×10^{10} Bq/g) is applied in medical treatments [26]. The typical dose of ^{90}Y administrated to a patient is 20–30 mCi with a circulation of the substance in blood [27]. The maximum admitted dose for the implants is 3 GBq (~80 mCi) for one medical treatment. These data can be used to roughly assess the ^{90}Y radioisotope price: the medical implants for treatment cost USD 11,000–12,000 [28]. This includes ~5–10% expenses for the isotope, that is, USD 550–1200/80mCi or USD 186,500–405,400/TBq (USD 6900–15,000/Ci).

^{153}Sm

Palliative care can include effective symptom and pain relief with such isotopes as ^{153}Sm [4] with a $T_{1/2}$ = 46.27 h. The importance of this isotope is increasing in radiological cancer treatment. The routine production of this isotope is carried out in small research reactors by means of the neutron irradiation of samarium enriched in ^{152}Sm up to 100%: ^{152}Sm(n,γ)^{153}Sm [6]. The target quartz capsule of 8 mm diameter and 50 mm length for irradiation is filled with 1 mg of the Sm_2O_3 and it is irradiated for 2–3 days. The

specific activity achieved at the end of the irradiation is 1.5×10^{13} Bq/g [6]. ^{153}Sm is administered in a dose of 37 MBq/kg (1 mCi/kg) delivered through intravenous injection during the 1 min treatment that leads to estimated pain relief duration from 4 up to 40 weeks [29]. The reference specific activity of approximately 1×10^{12} Bq/g is already sufficient for its practical use in medical treatments [30]. The typical prescribed dose for one medical treatment is 37 MBq/kg; therefore, a patient weighing 70 kg requires 2590 Bq (70 mCi), and the whole procedure could be repeated up to four times in one year, resulting in ~115 TBq/year (3100 Ci/year) only in the USA [10], and roughly doubled in the world. An estimated medical treatment with the ^{153}Sm source is USD ~12,000 per patient and the price for the ^{153}Sm isotope varies from USD ~378,380–729,730/TBq (USD 14,000–27,000/Ci) [31–33] depending on the supplier.

^{177}Lu

^{177}Lu ($T_{1/2}$ = 6.734 days) is a somewhat short-lived isotope with enormous applications in the medical industry [4], and its radioactive properties make it a powerful tool for the direct treatment of certain cancers. The production of ^{177}Lu is performed by direct neutron irradiation of enriched ^{176}Lu through neutron capture: ^{176}Lu(n,γ)^{177}Lu. The target material, Lu_2O_3, in the amount of 10 mg sealed in a quartz ampule of 8 mm diameter and 50 mm length and irradiated for 1 week can reach a specific reference activity of 2×10^{12} Bq/g [6]. The lutetium-176 with a natural abundance of 2.59% is usually used enriched up to ~70%. The price for the enriched ^{176}Lu can reach USD 220/mg [34,35] and the price for the ^{176}Lu radioactive source is estimated to be USD 1–2.2 M/TBq (USD 38,000–80,000/Ci) [36,37].

^{186}Re

^{186}Re ($T_{1/2}$ = 3.718 days) is used for bone pain palliative care [4,10]. This isotope is fabricated through neutron irradiation of ^{185}Re in the fission reactors: ^{185}Re(n,γ)^{186}Re. The target material, 1–12 mg of Re enriched above 94% of ^{185}Re, is enclosed in quartz capsules of 9 mm diameter and 50 mm length and it is irradiated for 7–10 days [6]. The reference specific activity achieved at the end of the irradiation is 3.7×10^{13} Bq/g [10]. The estimated annual demand of ^{186}Re in the USA is 148 TBq/year (4000 Ci/year) and it might be twice as high worldwide [10]. The dose of 1.5 GBq (40 mCi) is usually prescribed up to four times per year. Rhenium is the rarest stable nonradioactive element, and the price for the target material, ~97.4% pure ^{185}Re, is, accordingly, USD ~9500/g [35]. The ^{186}Re radioactive source price is found to be USD ~12,000/5.5 GBq, that is, USD ~2.2 M/TBq (USD 81,000/Ci) [38].

^{204}Tl

^{204}Tl ($T_{1/2}$ = 3.78 years) is applied in the industry for measurement of dust levels in technical filters and for calibration and assessment of the thicknesses of plastic, metal, rubber, and paper sheets. This isotope is typically produced in fission reactors through the neutron irradiation of the target material ^{203}Tl(n,γ)^{204}Tl. Metal thallium in the amount of 1 g is sealed in aluminum cans of 22 mm diameter and 50 mm length. The yield after neutron irradiation for 4 weeks, i.e., the reference specific activity, is as high as 3.75 mCi/g or 1.4×10^8 Bq/g. The ^{203}Tl target material is available on the market at the price of USD ~2200/g [35]. The ^{204}Tl small sources are offered on the market for USD 514/MBq to USD 12,430/MBq (USD 190/10 μCi to USD 115/0.25 μCi) [39].

3. Modeling Approach

3.1. DEMO Geometry Model with the Irradiation Unit

The DEMO baseline 2017 [40] is the basis for the MCNP model used here. The CAD geometry model of the DEMO tokamak with the irradiation port suitable for the neutronic calculations provides space for the arrangement of all tokamak elements that could potentially have an effect on particle transport calculations and, therefore, it is a prerequisite for production of the high-accuracy nuclear responses that are further used for the activation analyses. The newly created DEMO CAD model was elaborated to exclude,

as far as possible, small geometry details that could lead to an excessively complicated MCNP input deck and, as a result, they could potentially decrease the credibility of the converted models and very likely could, at the end, cause a failure in the particle transport calculations. To avoid potential problems in the final MCNP geometry model, the CAD layout includes those simplifications that do not contribute to the increase of the results' uncertainty but provide an adequate similarity with the original design. The conversion of the CAD model into the MCNP one was conducted with SuperMC code [41]. To simulate a full DEMO reactor, tokamak periodic boundary surfaces were assigned in the model. A verification and a validation of the newly developed model were performed through MCNP cell volume calculations. In spite of significant efforts, the final model contains a few tiny geometry errors, resulting in less than 5 lost particles per 10 million source neutrons. Such level of the geometry model credibility is considered sufficient to provide high-accuracy nuclear responses.

The MCNP model with the irradiation port integrated in the DEMO baseline model was developed to have a modular structure complying with a strict hierarchy for different geometry parts. The latest frozen layout of the Helium Cooled Pebble Bed (HCPB) breeder blanket [42,43] was used to fill the blanket space in the tokamak and to simulate a realistic environment for the irradiation port. The fully heterogeneous, well-detailed representation of the HCPB blankets with breeder units was manually arranged in the inboard and outboard blanket space of the DEMO tokamak, making use of the MCNP platform. The MCNP geometry model of the HCPB DEMO is a 11.25° toroidal sector containing inboard breeder (IB), outboard lateral (OBL) and a half of the central outboard (OBC) blankets (Figure 1).

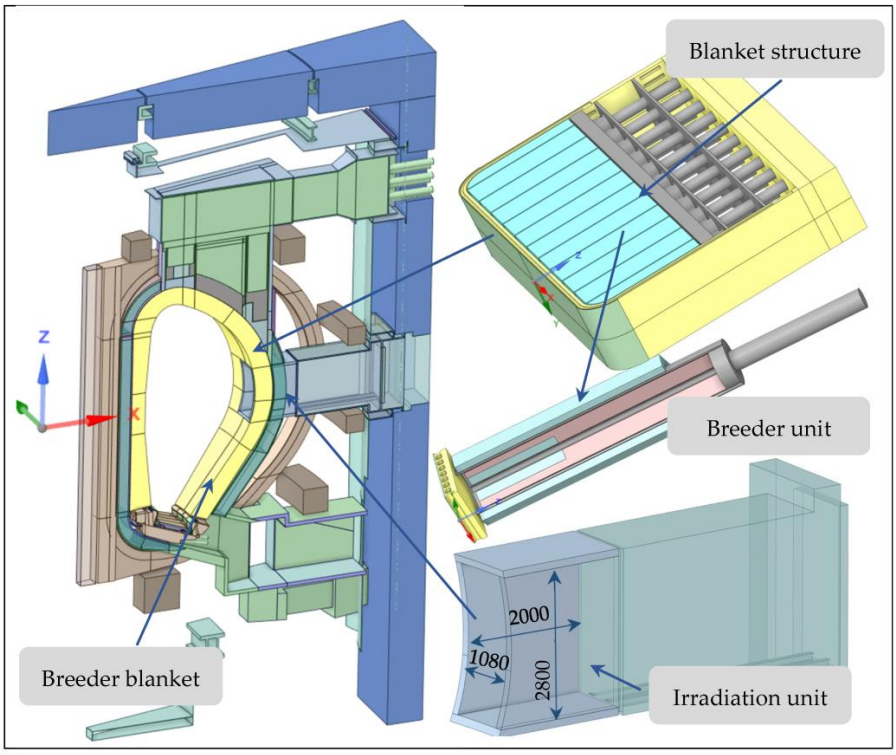

Figure 1. Geometry hierarchy in the MCNP geometry model.

3.2. Irradiation Unit Layout

The production of radioactive isotopes in the equatorial port of EU DEMO is currently not foreseen but is studied here as a potential option that could be introduced in the design at a later point in time. The concept and layout of a DEMO irradiation port is, therefore, not available in the DEMO project, and to this end, a preliminary design of the irradiation units and their integration in the port was developed for this work. The possible structure

of the unit assumes that the isotope production technique in DEMO could be similar to established techniques implemented in fission reactors. In most cases, the layout applied for the arrangement and the neutron irradiation of the precursor raw materials is close to conventional fuel pins or rods assembled in fuel bundles and enclosed in cassettes [6].

The irradiation port is assumed to have a double-wall structure with internal cooling water with total thickness of 140 mm (steel/water mixture). This provides the volume for the integration of the irradiation units for the isotope production. The size of the irradiation unit matches the DEMO equatorial port, which has a size of 2800 × 1080 × 2000 mm (H × B × L).

The principal dimensions of the irradiation rods come from the main design used for the ^{60}Co isotopes production in the CANDU reactor [6,23]. Shown in Figure 2 are basic options of the pin design that can be used as a basis for the diverse geometry modifications that can be applied for the fabrication of different radioisotopes. There are two options to allocate the metals for irradiation in the pin: (a) a metal pencil of ~6.5 mm diameter is placed in a SS316L steel container with a wall thickness of 0.8 mm, and (b) small metal pellets of 1 mm diameter and 1 mm length are allocated in an aluminum alloy Al-6061. The former option can also be used for the generation of various isotopes. Depending on the irradiation campaign duration, safety requirements for the rod design can be relaxed, that is, the rod can contain fewer protecting safety barriers or cylindrical layers against radioactivity leakage compared to the layout used for the cobalt irradiation (Figure 2c,d). In these cases, the material is enclosed in the capsule: (c)—aluminum and (d)—quartz. The outer diameter of the irradiation rods is 17 mm.

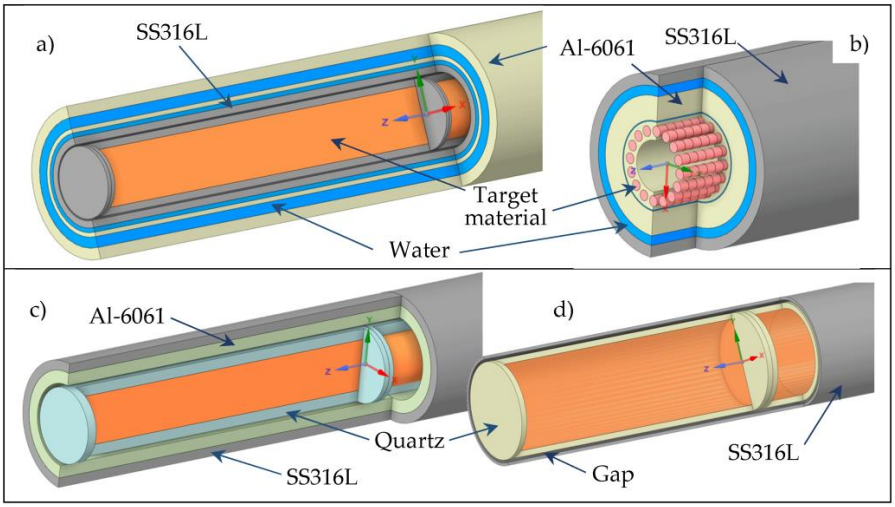

Figure 2. The layouts of the irradiation rods for the fabrication of different radioactive isotopes.

The rods containing initial material for the irradiation are bundled together to make up an assembly. This assembly contains 30 rods that are arranged in a hexagonal matrix with a pitch (distance between rods) of 11 mm (Figure 3). The whole assembly is enclosed in the hexagonal cassette with the outer size of 136 mm and the wall thickness of 4 mm. The rods are fixed inside the cassette with spacing grids. The central rod in the cassette is made of steel to reinforce the whole structure. The cassettes are installed in a radial direction from the plasma with a gap in-between of 5 mm; they fill the whole space of the irradiation unit, and they are mounted between supporting grids: plasma-faced and back one.

The irradiation port is separated from the plasma by a 25 mm thick first wall cooled by the pressurized water of 155 bar. The cooling of the irradiation assembly is assumed with low pressure water to enable the possibility of the cassettes' removal during the reactor operation, dwell, maintenance, or shut down. The design of the cell adjacent to the irradiation unit is out of the scope of the present work and it should be elaborated on separately to define an actuation system for the secure extraction of the cassettes. This

assumes the possibility to individually remove cassettes from the irradiation port, the remaining space in the irradiation unit being automatically filled with water.

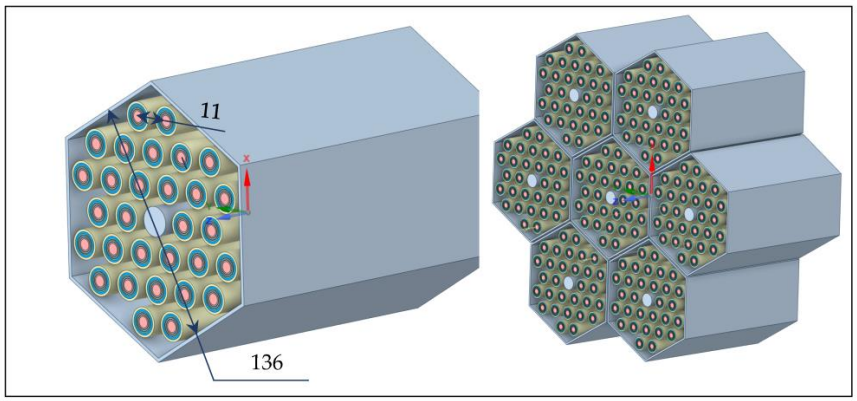

Figure 3. Irradiation cassettes.

3.3. DEMO MCNP Geometry with the Irradiation Unit

The development of the geometry model of the irradiation unit for the neutronic calculations was performed using the MCNP input deck with the help of the integrated tools for the geometry generation. In particular, the unit layout includes many structures with repeated patterns such as rods and cassettes arranged in the hexagonal lattice. For the modeling of this complex structure, a repeated structure function embedded in the MCNP was applied to replicate the geometry pattern of the rod and the cassette described above. Shown in Figure 4 are the section cuts of the MCNP geometry model for the separate rod and cassette integrated in the irradiation unit of the DEMO equatorial port. This MCNP geometry model built on the modular base enables quick replacement of the irradiation rod layout customized to different isotope production schemes. If needed, the whole irradiation unit layout can be also replaced without changing of the overall DEMO port layout.

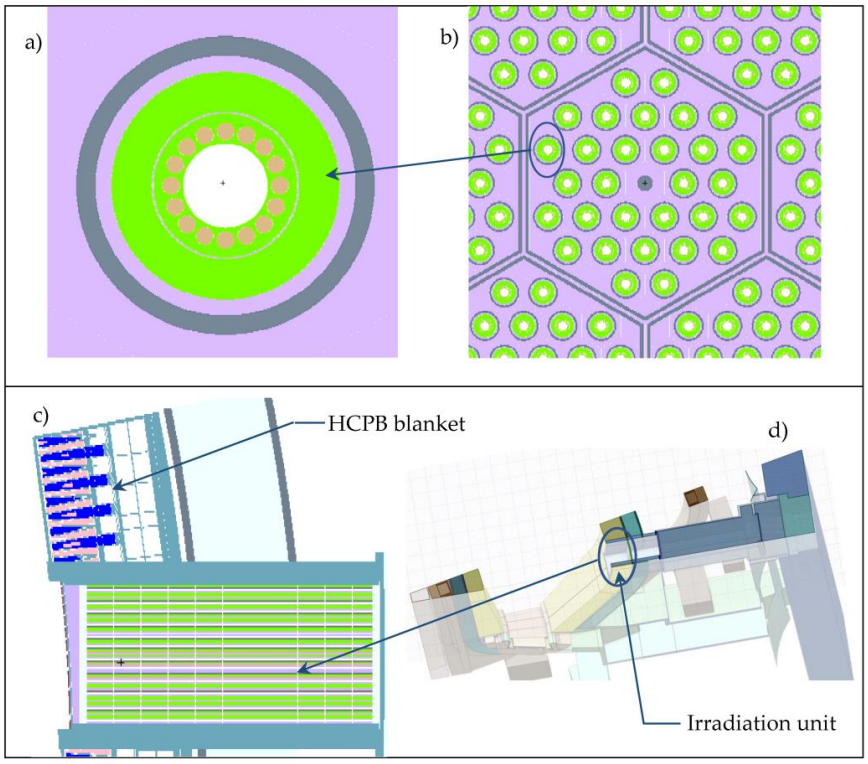

Figure 4. The cuts of the MCNP geometry models for irradiation rod (**a**), irradiation cassette (**b**), irradiation unit (**c**), and the cut of the DEMO CAD in the reactor midplane (**d**).

4. Computational Technique

4.1. Computer Codes and Nuclear Data

The assessment of the isotope production in the irradiation unit of the DEMO was conducted in two steps: (1) the assessment of the spatial distribution of the neutron spectra in the irradiation rods; (2) the activation analyses involving the neutron spectra to quantify the generation of the radioactive isotopes.

The neutron transport simulation (1) implies the calculation of the neutron spectra in all geometry cells of the irradiation rods where activation and depletion analyses are carried out. To enable this, each rod was subdivided in the radial direction into 50 mm long parts (the typical size of the irradiation capsule) to assess the radial distribution of the neutron spectra. This was achieved by applying the variance reduction technique, resulting in a low statistical uncertainty of the results, typically below 0.5%. The neutron flux intensities and the spectra necessary for the activation analysis were mapped over the irradiation unit geometry, making use of MCNP6.2 [44], CCFE 709 neutron energy group structure [45] to obtain accurate collapsed reaction rates and JEFF-3.3 nuclear cross-section data [46]. An explicit plasma neutron source description was introduced in the MCNP input deck involving the model developed in [47]. In the present study, only the accumulation and the time evolution of the generated radioactive isotopes inventories were analyzed. To this end, the neutron spectra were tallied only in the geometry cells containing precursor materials for the isotope production. Special attention was paid to the accuracy of the neutron flux calculations, and the achieved statistical uncertainty of the total neutron flux was less than 0.5%. For some low-energy bins, for instance, 1×10^{-7}–1×10^{-4} MeV, the relative error of the MCNP calculations was below 10%. The DEMO fusion nuclear power of 1998 MW [1] was taken for the normalization of the nuclear responses, which results in plasma neutron source intensity of 7.094×10^{20} s^{-1}.

The activation analyses, step 2, assume numerous inventory calculations. To support the study, a specially developed computer interface was applied to produce the final results [43]. The interface goes through the MCNP input file for the neutron transport calculations and picks up actual material compositions used in the calculations. For the execution of numerous FISPACT II [45] inventory calculations, the interface prepares specific input files using fine material composition and a proper irradiation scenario for the production of each radioisotope and submits them in parallel mode, making use of the MPI technique. The latest version, 2021, of the TENDL activation library [48] is used in the FISPACT II calculations. The results of the FISPACT inventory calculations are collected and processed by a post-processing code. Finally, the code provides the time evolution of the activity and decay heat in a separate cell and groups of cells, results for dominant nuclides, specific data such as masses, differential activity, and decay heat of the nuclides accumulated in the geometry cells.

4.2. DEMO Operation Scenario

The current DEMO design [1] assumes a 30% availability of plasma operation. During 70% of its operation phase, DEMO is assumed to be in shutdown or standby state [43,49]. Given the significant uncertainty of the DEMO operation schedule, the assessment of the commercial radioactive isotopes production is based on simplified irradiation scenarios. In the assessment of short-lived radioisotopes, a plasma operation period of 10 days (for most isotopes, see Section 2.3) or 35 days (for ^{131}I, ^{204}Tl, see Section 2.3) is assumed, made up by a sequence of 4 h plasma pulses interrupted by 1 h dwell (see Figure 5). In the production assessment of the long-lived isotope ^{60}Co, an irradiation period of 365 days was considered with 30% of the nominal fusion power. It is assumed that the ^{60}Co isotopes are removed after 365 days.

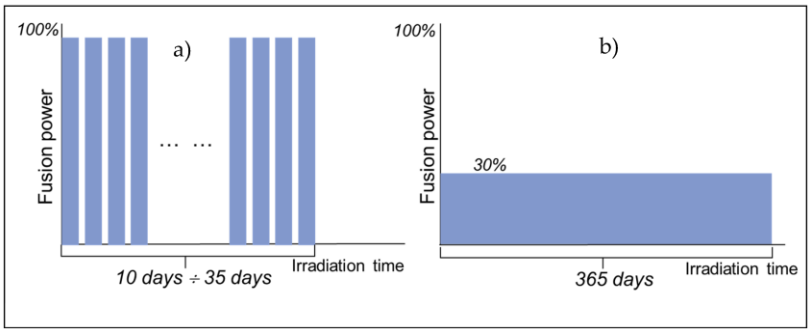

Figure 5. Irradiation scenarios considered in the assessment of the production of short-lived isotopes (**a**), and long-lived isotope ^{60}Co (**b**).

5. Results of the Inventory Calculations

A spatial accumulation of the radioactive isotopes in the rods along the radial direction was assessed for each radioactive isotope specified in Section 2.2, making use of the computational technique and irradiation scenarios discussed above. The maximum isotope production rate is expected in the radial segment of the rods adjacent or close to the plasma-faced supporting grid. The accumulated activity of the isotopes in the different locations in the rod depends on the radial coordinate of the segment or capsule. The efficiency of the isotope production in the irradiation port of the DEMO can be assessed by the comparison of the activity produced in the rods with the reference data discussed above (see Section 2.3). These reference data refer to the actual isotope production efficiency of the available commercial reactors; therefore, they represent the typical average isotope activity that is consumed on the world market. The spread of the specific activities over the reference value that can be utilized in the industry is significant. To keep a very conservative approach, the minimum value of the specific activity that could find an application and consumption in the medicine and industry is assumed to be ~10% from the reference value. Activity levels above the reference value have a very high potential for the practical applications because it allows the use of very compact radioactive sources. This approach is used for the assessment of the commercial yield of the radioactive isotopes in the DEMO irradiation unit. Nevertheless, the total isotope yields in the rods were calculated as well. No optimization of the isotopes production, that is, a variation of the geometry layouts and the irradiation duration, was implemented because the scope of the work was to demonstrate the principal capability of the radioactive isotopes production in the DEMO.

Shown in Figure 6 are the results for the production of ^{99}Mo and ^{192}Ir isotopes: the peak production in the front 5 cm part of the rod and the radial distribution of the isotope accumulation in the rods. The reference values of the typical isotope production are also given for the assessment of the commercial radioactive isotope yields. In both cases, the irradiation campaign amounts to 10 days (240 h) of the DEMO pulse irradiation, and the total number of the feasible campaigns is 11 per calendar year, assuming 30% of the total facility availability. The commercial yield is an integral of the production within 0–35 cm and 0–90 cm of the radial depth in the rods in the case of the ^{99}Mo and ^{192}Ir isotopes production, respectively. In these locations, the specific activity is higher than or equal to 10% of the reference activity level. The maximum specific activity of the ^{99}Mo achieved at the end of one irradiation campaign within the first 5 cm of the irradiation rods can reach 1.2×10^{10} Bq/g, which corresponds the maximum yield of 3.32×10^{2} TBq in all rods and cassettes. A so-called *six-day activity* (the activity after 6 days of the decay) often applied for the ^{99}Mo production is 4.40×10^{1} TBq (~1200 Ci) and the commercial yield is 1.40×10^{2} TBq (~3800 Ci) per one irradiation campaign of 10 days. The maximum production rate per 10-day irradiation period is ~60% of production in the Opal one (~2200 six-days Ci, see Section 2.2) having 15% of the world's market. The maximum specific activity of the ^{192}Ir that can be reached in the port is 6.0×10^{11} Bq/g

and the maximum yield is 3.00×10^1 TBq. The commercial yield in this case amounts to 1.92×10^2 TBq.

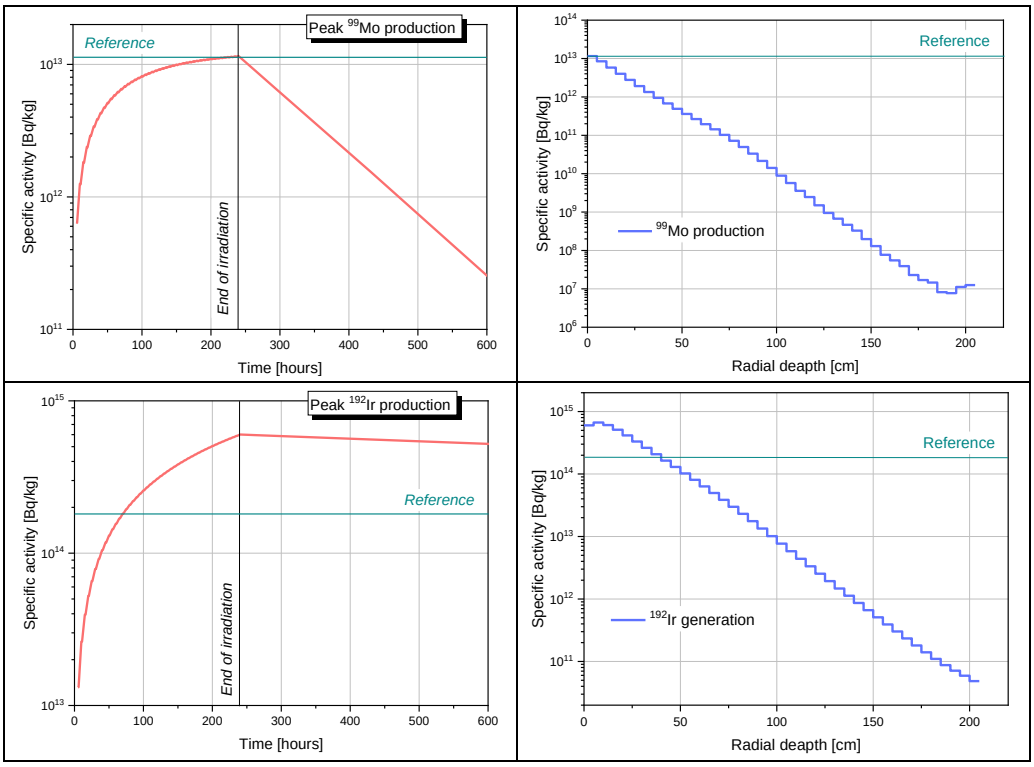

Figure 6. Accumulated specific activity of ^{99}Mo and ^{192}Ir isotopes: peak value and the radial distribution in the rods.

The results for the ^{103}Pd and ^{169}Yb production in the irradiation unit are given in Figure 7. The duration of the irradiation campaign in both cases is 10 days and the number of the campaigns per year is 11. The commercial yield is accumulated within 0–95 cm and 0–60 cm of the radial depth in the cases of the ^{103}Pd and ^{169}Yb isotopes, respectively. The maximum specific activity can achieve 2.7×10^{10} Bq/g and 3.2×10^{12} Bq/g in the case of the ^{103}Pd and ^{169}Yb production, respectively, which corresponds 1.20×10^1 TBq and 7.50×10^1 TBq of the maximum yield. The commercial yields are 7.65×10^1 TBq and 3.82×10^2 TBq for these isotopes, respectively.

The production of the ^{125}I and ^{131}I isotopes is shown in Figure 8. The maximum specific activity that can be accumulated in the irradiation rods appears to be 6.5×10^{14} Bq/g and 4.4×10^9 Bq/g for the ^{125}I and ^{131}I isotopes, respectively. The irradiation campaigns are 10 and 35 days for these isotopes. The yields for the commercial consumption can be produced within 0–60 cm and 0–35 cm in the irradiations rods for iodine 125 and 131, respectively. The maximum yields of these isotopes are 2.60×10^{-1} TBq and 1.05×10^3 TBq, and the commercial yields are 1.40×10^0 TBq and 5.30×10^3 TBq, respectively.

The production of the long-lived ^{60}Co isotope is a challenging option for the DEMO irradiation unit because the typical irradiation campaign of 1.5–3 years exceeds the duration of the first operation phase of the DEMO. To address the uncertainty of the DEMO operation, the availability factor of 30% is applied to simulate the irradiation campaigns. For the present work, the duration of the neutron exposure for the ^{60}Co generation was assumed to be 1 calendar year to compare the results with the typical end productions from different world suppliers. It is evident that DEMO cannot provide comparable irradiation conditions with the fission reactors, but it might be an opportunity for the long-term irradiation campaigns during the second operation phase. Presented in Figure 9 are the results for the ^{60}Co and ^{90}Y production. In the latter case, the irradiation campaign was set to 10 calendar days. The maximum specific activities achieved in the irradiation rods are

2.4×10^{10} Bq/g (maximum yield is 3.15×10^{2}) and 2.4×10^{10} Bq/g (maximum yield is 6.00×10^{2} TBq) for ^{60}Co and ^{90}Y production, respectively. The commercial yield is produced within 0–5 cm and 0–35 cm for these two isotopes, and the corresponding yields amount to 6.00×10^{2} TBq and 1.23×10^{3} TBq for the ^{60}Co and ^{90}Y production, respectively.

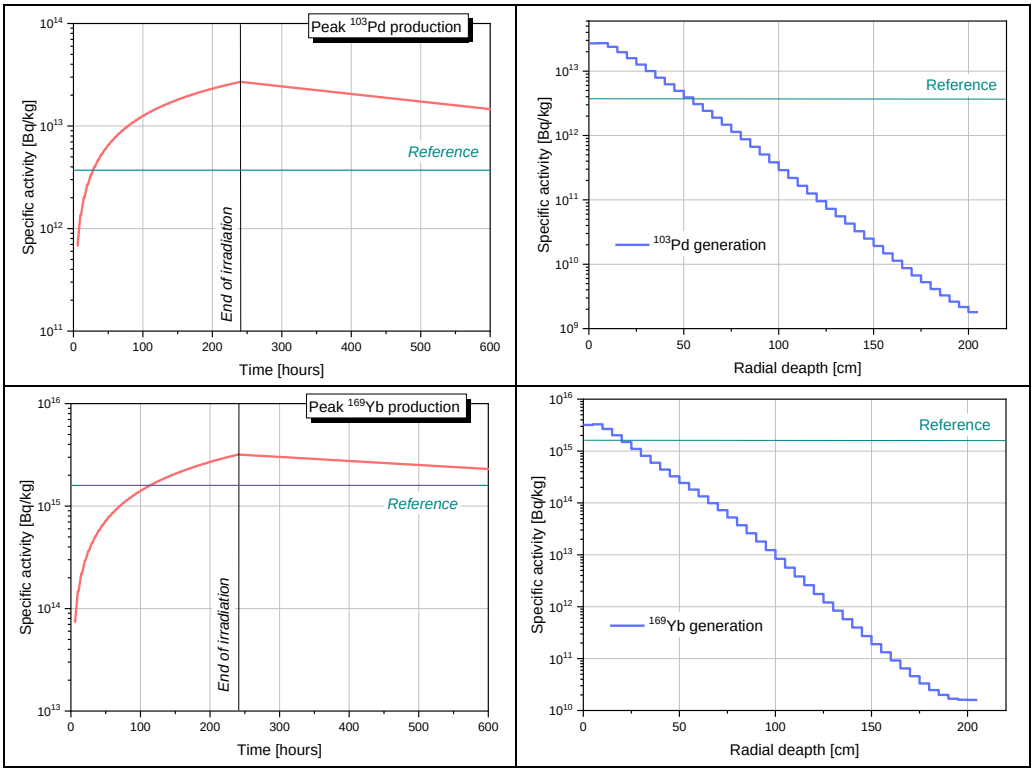

Figure 7. Accumulated specific activity of the ^{103}Pd and ^{169}Yb isotopes: peak value and the radial distribution in the rods.

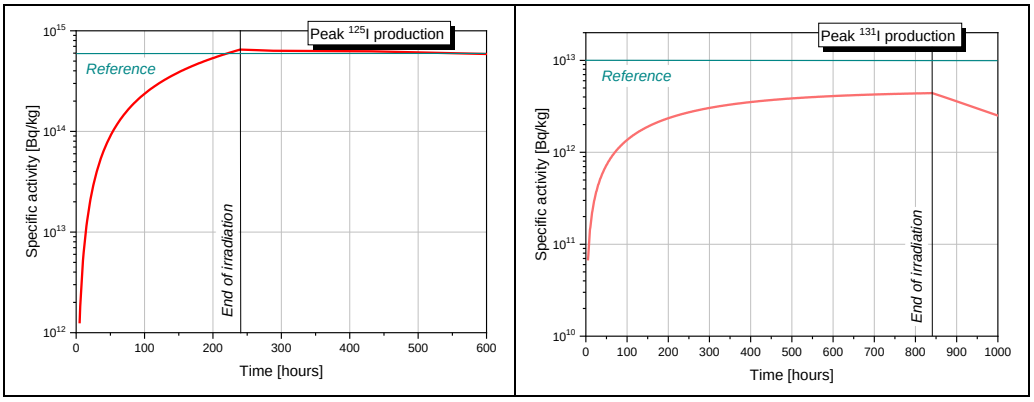

Figure 8. Peak values of the generated specific activity of the ^{125}I and ^{131}I isotopes.

The rare-earth radioactive ^{153}Sm and ^{177}Lu isotopes are expensive and their world production is very limited. The results of these isotopes' production in the irradiation unit are shown in Figure 10. In both cases, the campaign is 10 calendar days of pulse irradiation. The maximum accumulation of ^{153}Sm and ^{177}Lu in the rods is below the reference values; assuming the accepted criterion of 10% of the reference activity, some generation of these isotopes is, nevertheless, still possible. In case of ^{153}Sm, the commercial yield could be expected in the rods within the first 0–25 cm, and in the case of ^{177}Lu, it is produced with 0–35 cm. The maximum accumulated specific activities are 5.2×10^{12} Bq/g and 9.3×10^{11} Bq/g for the ^{153}Sm and ^{177}Lu, respectively, and the integral maximum yields amount, respectively, to 1.00×10^{1} TBq and 3.87×10^{1} TBq. The noticeable commercial

yields could be accumulated within the specified radial depths of the rods: 3.17×10^1 TBq and 1.83×10^2 TBq for ^{153}Sm and ^{177}Lu, respectively.

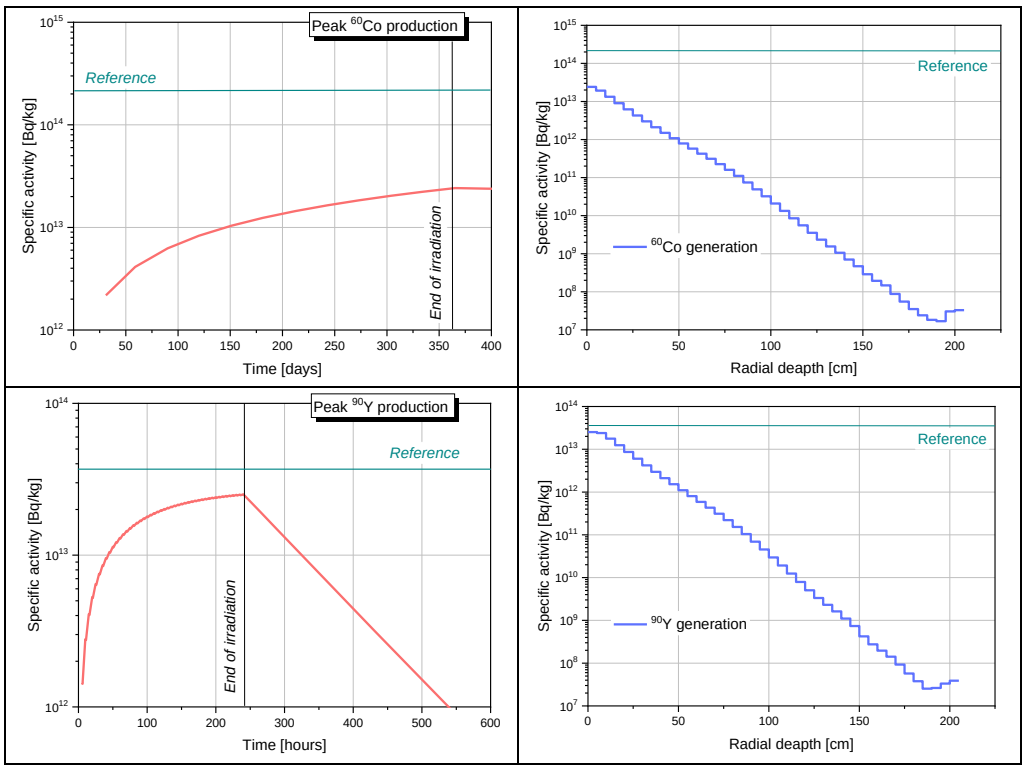

Figure 9. Accumulated specific activity of the ^{60}Co and ^{90}Y isotopes: peak value and the radial distribution in the rods.

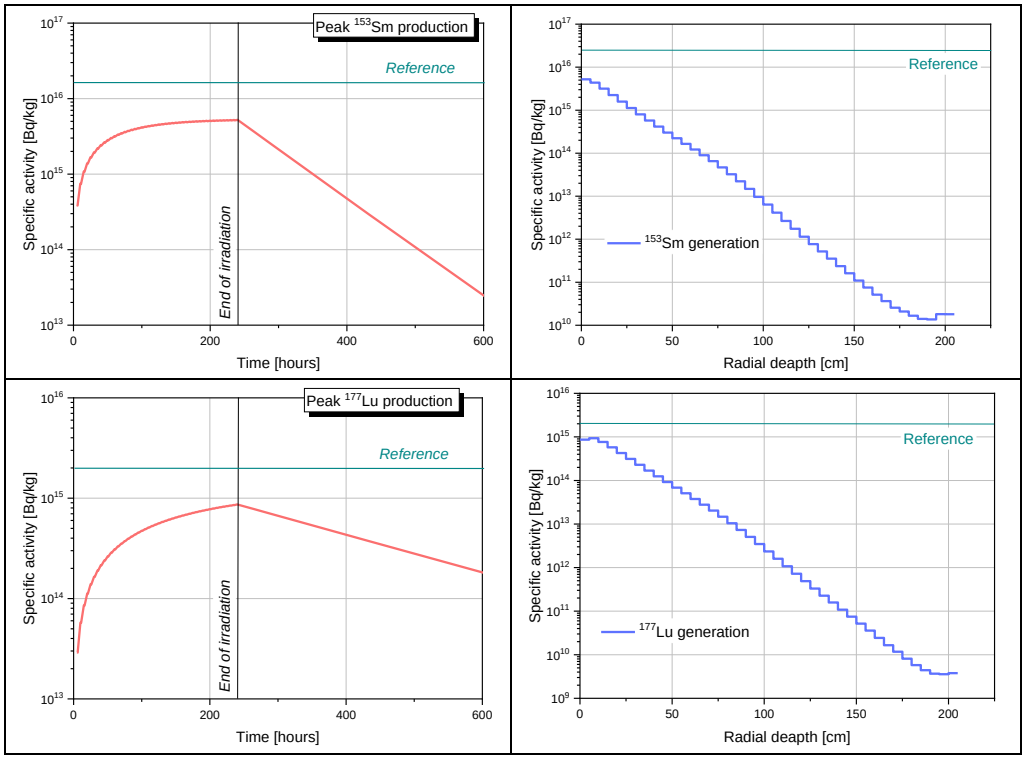

Figure 10. Accumulated specific activity of the ^{153}Sm and ^{177}Lu isotopes: peak value and the radial distribution in the rods.

The results for the ^{186}Re and ^{204}Tl production are presented in Figure 11. The duration of the irradiation campaign in these cases amount to 10 days and 35 days, and the number of the campaigns achieves 11 and 3 per year for the ^{186}Re and ^{204}Tl, respectively. The maximum accumulation of ^{186}Re in the rods is 2.0×10^{12} Bq/g; it is well below the reference value (3.7×10^{13} Bq/g) and no commercial yield is expected for this isotope. The commercial yield for ^{204}Tl is accumulated within 0–100 cm of the radial depth. The maximum accumulation of the ^{204}Tl is 1.16×10^{9} Bq/g (maximum yield is 8.82×10^{0} TBq), and the commercial yield of this isotopes would be as big as 5.57×10^{1} TBq.

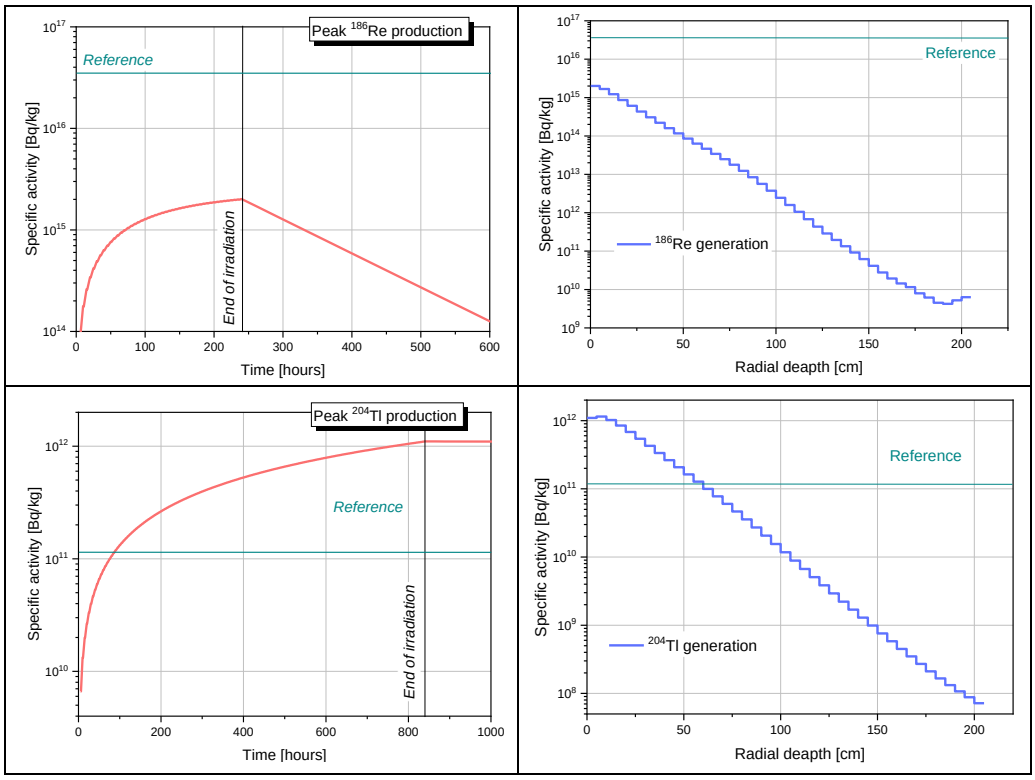

Figure 11. Accumulated specific activity of the ^{186}Re and ^{204}Tl isotopes: peak value and the radial distribution in the rods.

The results of the assessment of the radioactive isotope production in one DEMO irradiation unit are summarized in Table 1. The duration of the irradiation campaigns applied in the calculations is discussed in Section 2.2; the feasible number of campaigns per year is calculated, assuming 30% plasma neutron source availability. The maximum yield per one campaign denotes the maximum activity produced in one radial segment with the highest specific activity in the irradiation rod to enable the comparison with the typical productions in the reactors. Because of the depletion of the isotopes' production along the radial depth in the rods, the value of the lumped commercial yield during one campaign is introduced to show the DEMO potential to generate radioactive isotopes that could find the industrial consumption irrespective of the specific activities of the separate samples. Naturally, no produced isotopes are allowed to be wasted in this facility; therefore, it is also supposed that all activated samples could find reasonable application in the world economical market and, therefore, the total isotope yield, i.e., integral production along the full rod length, is also assessed for 1 calendar year of the DEMO operation, assuming specified number of the irradiation campaigns. For this option, no financial considerations are applied. The estimated wholesale prices (presented as USD) are given in Table 1 to give a survey of the potential product prices on the world market. Because of the very small commercial yield in the case of ^{60}Co and no commercial yield in the case of ^{186}Re, this assay was performed for these isotopes making use of the total yield, i.e., the production on the full rod length.

Table 1. Assessment of the annual production capability of different radioactive isotopes. Values assume one DEMO irradiation unit dedicated exclusively to the production of one isotope.

Isotope	$T_{1/2}$	Irradiation Campaign, Days [Camps./Year]	Max. Specific Activity [Reference] Bq/g	Max. Yield [1], Comm. Yield [2], [Yield/Year] TBq	Market Price, M USD/Year
^{99}Mo	65.94 h	10 [11]	1.2×10^{10} [1.2×10^{10}]	4.4×10^{1} * 1.4×10^{2} * [1650]	10–30
^{192}Ir	73.83 days	10 [11]	6.7×10^{10} [6.8×10^{10}]	3.0×10^{1} 1.9×10^{2} [2200]	20–60
^{103}Pd	16.99 days	10 [11]	2.7×10^{10} [3.7×10^{9}]	1.2×10^{1} 7.6×10^{1} [847]	20–90
^{169}Yb	32.026 days	10 [11]	3.2×10^{12} [1.6×10^{12}]	7.5×10^{1} 3.8×10^{2} [4290]	20–70
^{125}I	59.408 days	10 [11]	6.5×10^{14} [6.0×10^{14}]	2.6×10^{-1} 1.4×10^{0} [16]	15–55
^{131}I	8.04 days	35 [3]	4.4×10^{9} [1.0×10^{10}]	1.1×10^{3} 5.3×10^{3} [18,000]	40–200
^{60}Co	5.2714 years	365 [1]	2.4×10^{10} [2.2×10^{11}]	6.0×10^{2} 6.0×10^{2} [2200]	0.1–30
^{90}Y	64.0 h	10 [11]	2.5×10^{10} [3.7×10^{10}]	3.2×10^{2} 1.2×10^{3} [15,400]	5–140
^{153}Sm	46.27 h	10 [11]	5.2×10^{12} [1.5×10^{13}]	1.0×10^{1} 3.2×10^{1} [429]	5–140
^{177}Lu	6.734 days	10 [11]	8.7×10^{11} [2.0×10^{12}]	3.9×10^{1} 1.8×10^{2} [2310]	50–220
^{186}Re	3.718 days	10 [11]	2.0×10^{12} [3.7×10^{13}]	2.7×10^{1} - [1210]	20–400
^{204}Tl	3.78 years	35 [3]	1.2×10^{9} [1.4×10^{8}]	8.8×10^{0} 5.6×10^{1} [168]	5–140

[1] The 5 cm sample with the maximum specific activity. [2] The lumped production in all radial segments of the rods with the specific activity above 0.1 × Reference. * Six-day activity.

6. Safety Considerations

The accumulation of high-level activity in the DEMO irradiation port was quantified to allow an assessment of potentially required safety measures in the DEMO facility. To provide a basis for this assessment, the amount of radioactivity in the irradiation unit was assessed. The maximum total generated activity in the unit during one irradiation campaign was found to be ~6×10^{15} Bq (the commercial yield is 5.3×10^{15} Bq) in the case of the ^{131}I production (Table 1). This is about 100 times less compared to the activity of the $Be_{12}Ti$ accumulated in one HCPB blanket segment during the first phase of the DEMO

operation [43,50] and it is ~10 times less compared to the $Be_{12}Ti$ activity between plasma pulses. A decay heat resulting from the ^{131}I generation does not exceed ~3 kW in all rods and cassettes, which is much less compared to 7 kW of the decay heat produced in one breeder blanket segment of the HCPB during its removal from the reactor [51]. In the case of the HCPB blanket, this does not result in a temperature higher than 50–80 °C.

7. Discussion

The use as irradiation port of one of the 16 equatorial ports of the DEMO tokamak was considered. This port should include at least two essential parts: the space for the isotope production, i.e., the irradiation unit, and the associated port cell hosting robots, drive mechanisms, and special equipment. The modeling of the irradiation unit is the subject of this work. The layout of the port cell is out of the scope of this paper. Starting from the CAD model of the DEMO baseline 2017, the MCNP geometry model with the integrated irradiation unit and adjacent breeding blanket volumes modeled according to the HCPB concept was used for the comprehensive analyses.

The numerical simulations were conducted with MCNP code for the assessment of the neutron spectra in the irradiation rods, and FISPACT II was used for the inventory calculations to obtain the material compositions after the specified neutron irradiation. The irradiation campaigns were chosen on the basis of the available information for the commercial isotopes' production in fission reactors and were customized to the foreseen operation of EU DEMO.

The assessment of the radioisotopes' production was carried out for 12 different nuclides with half-lives ranging from tens of hours to several years. Several nuclear responses were obtained to figure out the possible outcome of the neutron irradiations in the DEMO port: radial distributions of the accumulated activity of the isotopes along the radial depth of the rods, the maximum achievable specific activity of the isotopes (Bq/g), and the eventual yields of the isotopes (commercial and total in Bq).

The efficiency of the generation in the DEMO irradiation unit is different for various isotopes. The highest efficiency was found in the production of the short-lived ^{192}Ir, ^{103}Pd, and ^{169}Yb isotopes ($T_{1/2}$ = 17–73 days). Also, technically feasible but with a lower predicted efficiency, was the production of the ^{99}Mo, ^{125}I, ^{131}I, ^{90}Y, ^{153}Sm, ^{177}Lu, and ^{204}Tl ($T_{1/2}$ = 46 h–3.8 years). The production of ^{60}Co and ^{186}Re isotopes was found to be less attractive because the specific activity level of these isotopes typically produced in the reactors was not reached in EU DEMO. The layout of the irradiation port allows theoretically simultaneous, parallel production of several isotopes even with different half-lives. This flexibility of the irradiation unit operation also opens the possibility for research activities to pursue the generation of promising and rare radioactive isotopes for future medical and industrial applications.

The scope of this research work was also to estimate the possible financial potential of the irradiation unit in the case of industrial utilization of the generated isotopes. The eventual profit coming from the radioactive isotopes' production could make the DEMO project economically more attractive. To this end, the approximate market price of the final raw product for each isotope was assessed, making use of the available open sources. The estimate of the actual financial gain is complex and it is out of the scope of this work.

The use of the irradiation unit of ~6 m^3 volume integrated in the DEMO equatorial port for the production of radioactive isotopes could theoretically provide a significant financial outcome up to several hundred million USD per year. The DEMO operation in such dual mode (energy and isotope productions) could make the project more attractive also because the end use of the isotopes in medicine could highlight another socially well-appreciated aspect of the fusion energy. Therefore, with the new design option, the DEMO project could become more complex, which, nevertheless, could finally increase the attraction of the fusion energy.

8. Conclusions

Within the framework of the research work aimed at the development of the DEMO tokamak layout, numerical simulations were carried out to assess the potential to produce various radioactive isotopes for medical and industrial applications in one equatorial port. To perform the analyses, the very detailed geometry model of the irradiation unit was developed and integrated in the equatorial port of the DEMO generic model to conduct the accurate neutronic and the inventory simulations and to provide the nuclear responses to determine the radioactive isotopes' production. The developed MCNP geometry model of this optional tokamak configuration also includes a detailed model of the breeder blanket based on the HCPB BB concept.

The most basic system response, i.e., the accumulated specific activity of the isotopes, was assessed. Depending on the choice of isotopes being produced, their market value is predicted to be in the range of USD 10s to a few 100s of M per calendar year of DEMO operation. The development of the irradiation unit is only schematic thus far. Only the most basic parameters, such as its volume, were defined at this point as a prerequisite for further analyses. The continuation of this activity should include the development and identification of design, technologies, and operation concepts of the irradiation unit, an optimization of the irradiation schemes, and a comprehensive study of different safety and economical aspects. Should such a development be successful, the DEMO project could significantly gain economic and social acceptance if an irradiation cell was implemented.

Author Contributions: Conceptualization, P.P., C.B. and J.E.-U.; Methodology, P.P.; Software, P.P. and J.H.P.; Validation, P.P.; Formal analysis, P.P.; Investigation, P.P.; Resources, C.B.; Data curation, P.P. and J.H.P.; Writing—original draft, P.P.; Writing—review & editing, C.B., J.E.-U. and J.H.P.; Visualization, P.P.; Project administration, C.B. and J.E.-U.; Funding acquisition, C.B. and J.E.-U. All authors have read and agreed to the published version of the manuscript.

Funding: This work was carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200—EUROfusion). Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to copyrights reasons.

Acknowledgments: This work would not be possible without intensive use of the high-performance computing (MARCONI) recommended in the fusion roadmap as an essential facility to support basic research and the modeling efforts for the various objectives. We would like to also acknowledge support from the KIT-Publication Fund of the Karlsruhe Institute of Technology.

Conflicts of Interest: The authors declare no conflict of interest.

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