ARC reactor: Radioactivity safety assessment and preliminary environmental impact study

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The Affordable Robust Compact (ARC) reactor is a conceptual design for a Tokamak conceived by Massachusetts Institute of Technology researchers. The ARC design is under development and update.
Since ARC will be a D-T tokamak, neutron generation and material activation will be main issues for safety studies and assessment of environmental impact and siting questions. The safety assessment goal for ARC is to demonstrate that it could be easily sited in the US, without public health and environmental problems and the need of any emergency plan implying population evacuation or sheltering. Another safety feature that will be verified is the need of a containment building in which the reactor should be surrounded. Starting from activation studies already developed for the ARC's vacuum vessel structure and the liquid blanket as well, a further and deeper analysis, that includes the first wall and neutron multiplier layer activation, has been carried out. Afterwards, taking advantage of the RESRAD population dose code, the study arrives to the assessment of doses to most exposed individuals from accidental activated material release in atmosphere, including possible tritium releases: radioactive safety limits for ARC environmental impact are finally defined.

Keywords: Affordable Robust Compact (ARC), Tokamak, Safety, Activation, RESRAD

1. Introduction

Affordable Robust Compact (ARC) reactor is a conceptual design for a Tokamak proposed by Massachusetts Institute of Technology (MIT) researchers [1], [2]. The ARC design is under development and update. A nuclear licensing procedure, that includes radioactive safety assessment and environmental impact, must be followed before building a machine.

In this framework, the main safety objectives are based on international guidelines and are similar to those adopted by any fission nuclear facility [3], [4]. They are, in general, inspired by these principles:

- to protect workers, the public and the environment from hazards;
- to minimize releases to the environment of radioactive and other potentially hazardous substances, in gaseous, liquid, or aerosol form during normal operation;
- to minimize the frequency of plant failures that could initiate an accident sequence, and to reduce the potential consequences of all off-normal situations;
- to demonstrate that the favourable safety characteristics of fusion permit a safety approach that limits the hazards from accidents such that there is no need of any emergency plan implying population evacuation or sheltering;
- to minimize radioactive waste hazards, quantity and its level of activation and contamination, and ensure a safe and long-term disposal.

Concerning ITER, its successful licensing experience is of particular value as reference case for other fusion reactors [3]. The ITER project has developed a safety case, produced a preliminary safety report and had it examined by the French nuclear safety authorities, leading to the license to construct the facility [3], [4]. Concerning other nuclear fusion projects, some studies have been developed for the Ignitor experiment, a proposed compact high-magnetic field tokamak. In [5], major accident sequences for Ignitor were identified, analyzing the deterministic consequences of two accidental sequences, serving as the "design basis accidents" because of the extent of radioactive release involved, either outside or inside the building [6].

In this work, a preliminary estimate of ARC tritium inventory has been carried out for the first time. In addition, starting from activation studies developed for the ARC's vacuum vessel structure and the liquid blanket, the nuclide inventory has been evaluated. Afterwards, preliminary environmental impact studies have been developed, identifying which accidental sequences are likely to be analyzed in a Safety assessment, evaluating doses to population for reference radioactive releases. From these preliminary analyses, we can foresee the real possibility that ARC could ideally become the first less-than-one-tritium-kilogram power reactor. Even taking into account its experimental (demonstration) nature, the ARC experimental nuclear reactor connected to the electric grid could be easily sited in the US, without particular licensing questions and with no need for any emergency plan implying population evacuation, sheltering, or food consumption limitations.

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2. Radioactivity inventory

2.1 Tritium inventory

A main source of radiological hazard in ARC is tritium: it is a main fuel for the DT fusion reaction, a radioactive isotope not available in nature and that it is supposed to be provided by a full breeding, extraction and injection cycle. For tritium, a preliminary evaluation of inventory has been carried out. More specifically, the constant circulating inventory has been computed applying the mass balance equation [7]:

$$\frac{\eta \cdot f_b \cdot TBR}{t_p} \cdot M_0 = \dot{M}_1 + (\gamma_s + \gamma_r) \cdot M_0 \tag{1}$$

where η is the injection efficiency, f_b is plasma's burnup fraction; TBR is the tritium breeding ratio; t_p is the time needed to cleanup and recycle the tritium; M_0 is the time-independant, recirculating tritium inventory; $\dot{M}_1$ is the tritium burn rate needed to power the plant; γ_s is the decay losses coefficient and γ_r is the loss due to a non-ideal and perfect reprocessing of unburnt tritium.

In this framework, the inventory of interest is given by M_0 as it is the amount of tritium constantly circulating in the reactor and blanket side of the plant. Very high fueling efficiency values ($\eta \approx 0.9$) have been claimed in the past [8], but more recent studies (Report of the 4th IAEA DEMO Programme Workshop, 2016, Karlsruhe, Germany) show that these values may be lower ($\eta < 0.5$) Hence, a worst-case scenario assuming $\eta = 0.25$ and a best-case scenario assuming $\eta = 0.5$ have been considered for the calculations.Similarly, a tritium recovery time of t_p = 6h and t_p = 1h were chose for the worst-case and the best-case respectively. ARC's tritium breeding ratio has been provisionally estimated to be around 1.08 [2]: with a fusion power of 525 MW, ARC needs $\dot{M}_1 \approx 9.3e\text{-}7$ kg/s. Furthermore, assuming a well-designed and sufficiently efficient recycle system and knowing that the timescale for breeding and burning tritium is low with respect its half-life, the two losses γ_s and γ_r can be considered – for this initial evaluation - negligible [7]. The burnup fraction fb has been evaluated by equations (2) [7] and (3) [9]:

$$f_b = \frac{<v\,\sigma> n_0\, \tau^*}{1 + <v\,\sigma> n_0\, \tau^*} \tag{2}$$

$$f_b = \eta \cdot 10^{14} \cdot (1 + S_n) \cdot \tau^* \cdot n_0 T_0^2\, I \tag{3}$$

where $<v{\cdot}\sigma>$ is the velocity averaged cross section, n_0 is the on axis density, S_n is the ratio between the ions on axis density and the average density, I is directly proportional to plasma power and inversely proportional to n_0, T_0 squared and plasma volume [9]; and τ^* is equal to:

$$\tau^* = \frac{\tau_e}{1-R} \tag{4}$$

where τ_e is the energy confinement time and R is the ion recombination.

For ARC, most of the data can be found in [1] and [2]. Figure 1 and Figure 2 displays M_0 evolution for different TBR and f_b values, assuming a tritium recovery time of six and one hour respectively.

From ARC's characteristics it is possible to evaluate the burnup fraction $f_b \approx$ 2-3 % and, finally, a recirculating tritium inventory of M_0 = 2-8 kg for the worst case scenario and M_0 = 0.2-0.7 kg for the best case. Tritium inventory changes dramatically depending on the case under consideration. ARC is designed to exploit the most advanced technologies in the nuclear fusion field, hence, it looks reasonable to assume the best-case scenario as the reference scenario for this work. This means that hypothetically, ARC could be able to have 71-250 PBq of tritium inventory over the entire blanket and extraction systems. However, this preliminary analysis has been made in ideal conditions and does not take into account for tritium retention in ARC core and blanket loop materials. It is therefore possible to state that the current evaluation identifies the minimum tritium inventory present in ARC.

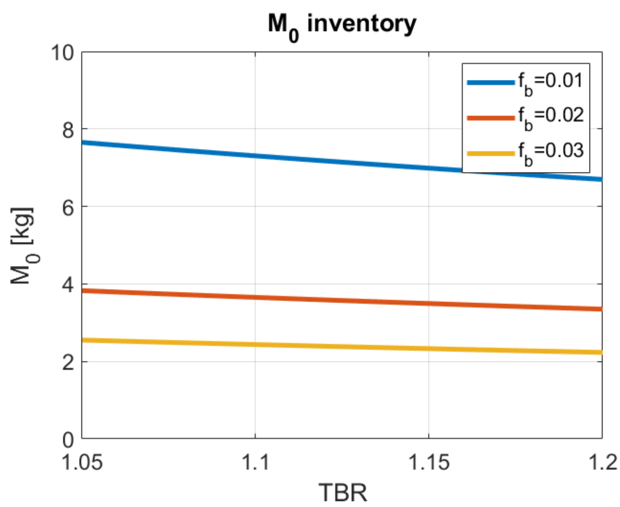

Figure 1 - Time independent recirculating tritium inventory as a function of TBR and burnup fraction, for η=0.25 and t_p = 6h.

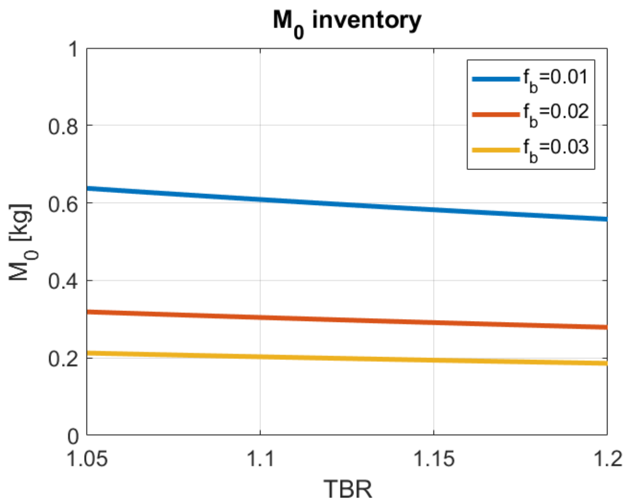

Figure 2 - Time independent recirculating tritium inventory as a function of TBR and burnup fraction, for η=0.5 and t_p = 1h.

2.2 Activated vacuum vessel

The other main source of radioactivity in ARC's plant is activated materials due to neutron fluence. This effect is therefore limited just to the machine's vacuum vessel and blanket. Concerning the vacuum vessel, ARC is designed to have a double walled chamber made of Inconel 718, a 1 mm thick tungsten first wall and a 10 mm thick beryllium layer as neutron multiplier [2]. The present work is focusing on low activation materials for ARC [10] and on the removal of the beryllium layer [11]. In this framework, a FISPACT – II activation model has been set up [12], run in multigroup mode and integrated with the ENDF/B-VIII library [13]. The model provides a low activation vessel option that it is assumed to be optimized by isotopic tailoring techniques. Table 1 describes vessel's main characteristics, where FW stands for first wall, STR1 is the inner structural layer and STR2 is the outer structural layer of the vessel.

Table 1. Main characteristics of proposed vacuum vessel configuration.

	V [m^3]	mass [kg]
FW	0.2	3,847
STR1	1	6,118
STR2	6.15	37,500
Total	7.35	43,623

In particular, the first wall is isotopically tailored with W-184. Structural material is the low activation alloy V-15Cr-5Ti, with Cr-52 and Ti-50 tailoring. FISPACT-II also requires the neutron flux on each component, the energy spectra and the irradiation time. Flux and spectra have been computed by means of an MCNP ARC core model [2], [14]. The component is designed to be replaced after two years. Hence, the FISPACT model foresees an irradiation time of 2 full power years, as worst-case scenario from the activation viewpoint. Some results of the FISPACT simulations are listed in Table 2. Those radioactivity values seem very high (thousands of Sv/h of contact dose rate as a minimum), but they refer to the final shutdown instant: a few minutes/hours of decay are enough to reduce all values by several orders of magnitude [10].

Table 2. Vacuum vessel activation results at shutdown.

	N flux [n/s/cm^2]	Total activity [Bq]	Contact dose rate [Sv/h]	Inhalation dose [Sv/kg]
FW	7.55E+14	2.74E+18	1.55E+03	5.61E+04
STR1	7.32E+14	1.77E+18	8.13E+04	3.71E+04
STR2	5.11E+14	5.27E+18	4.56E+04	1.41E+04
Total	-	9.78E+18	-	-

2.3 Activated breeder

The second activated component of the machine is the blanket. ARC's blanket is a beryllium fluoride molten salt (FLiBe) that continuously flows between the vessel walls and in a tank inside the magnets, where also the vessel stands. FLiBe has two inlet sections in the main chamber's channel, namely in the high and low field sides, it also has inlets in divertors. The fluid is supposed to flow at roughly 2 m/s in the mentioned channels [2] and then flow into the tank, which has a volume of 350 m^3. From a mass balance it was possible to come up to the irradiation time, that is 3 seconds in the vessel and about 100 s of fluid permanence in the tank, with a neutron flux of 7.3e+14 and 8e+13 n/cm^2/s, respectively. Moreover, the permanence time outside the tokamak for covering the entire loop has been evaluated to be one hour: FLiBe is irradiated for about 103 seconds per hour. Table 3 lists activation results after two years of irradiation, like the vessel, even though the whole permanence time of the salt in the plant has not been evaluated yet. Similar reasoning to the vacuum vessel results lead to the conclusion that the activity in FLiBe is acceptable. Furthermore, FLiBe requires much less time than the vacuum vessel materials to decrease below acceptable levels. [10]

Table 3. Liquid blanket activation results at shutdown

	Mass in the tank [kg]	Total activity [Bq]	Contact dose rate [Sv/h]	Inhalation dose [Sv/kg]
FLiBe	679E+03	3.32E+19	4.57E+04	1E+03

2.4 EST (Environmental Source Terms)

To determine the maximum releasable inventories the following source terms must be taken into account:

• Tritium located in components liable to eventual mobilization and release in case of accident, in HTO or HT form.

• Dust (Activated Products, AP): it is produced and accumulated in the VV: Particles of the size of μm, concretionary drops and flakes (mainly tungsten and stainless steel) coming from plasma wall interaction in normal operation, as well as in off normal and accidental events (e.g. disruption). Large fraction of the dust inventory can be easily mobilised.

• Activated Corrosion Products (ACPs): accumulated mainly in the cooling loops due to the corrosion/erosion action of the coolant. The mobilisable fraction is in general only a few percent of the total inventory.

3. ARC Safety Goals

Concerning the safety of individuals, society and the environment, the potential hazards in ARC from normal operation, off-normal operation and waste are addressed as follows:

(1) Ensure in normal operation that exposure to hazards within the premises, as well as exposure to hazards due to any hazardous effluents from the premises, is controlled, kept below prescribed limits, and minimized;

(2) Prevent accidents with high confidence and ensure that the consequences, if any, of more frequent events are minor and that the likelihood of accidents with higher consequences is low;

(3) Demonstrate that the consequences from internal accidents are bounded so that, according to US regulations, there is no need for evacuation of the public, and no measures on food consumption too.

(4) The results in (1) and (3) have to be obtained without the need of an auxiliary fission-reactor-like containment building for the reactor. To be verified.

(5) Reduce radioactive spent materials hazards and volumes. No High-Level Waste (HLW) is produced.

External hazards are site dependent, but will be considered for a generic US site. Concerning (3), the favourable characteristics of ARC justify the goal of having, even for hypothetical events with extremely low frequency, the calculated doses to the local population below 10 mSv (early dose, i.e., avertable dose within a period no more than 1 week). Following site selection, host US State regulations will apply. Likewise, HLW definition may vary with national legislation: the US Code of Federal Regulations (CFR) will be taken as a reference.

In order to obtain the above results, Maximum Allowable Radioactivity Releases (MARRs) to the environment can be estimated for a generic site. The MARRs are aimed at ensuring margins between calculated values and safety goals.

- For events or conditions dealing with normal operation, including events sequences and plant conditions planned and required for ARC normal operation, and including some faults, events or conditions which can occur as a result of the ARC experimental nature, releases shall be reduced to levels as low as reasonably achievable, and ensure they do not exceed project release guideline for Normal Operation (it will be computed later, see section 5), that is, < 2 g of T as HT and 0.2 g of T as HTO, per year.
- For incidents, i.e. deviations from normal operation, event sequences or plant conditions not planned but likely to occur due to failures one or more times during the life of the plant but not including Normal Operation, likelihood and magnitude of releases shall be reduced, to ensure they do not exceed project release guideline for Incidents: < 2 g T as HT or 0.2 g T as HTO, per event.
- For Accidents, comprising postulated event sequences or conditions not likely to occur during the life of the plant, likelihood and magnitude of releases shall be reduced, to ensure they do not exceed project release guideline for Accidents: < 20 g T as HT or 2 g T as HTO, per event.

HT: elemental tritium (including DT); HTO: tritium oxide (including DTO).

Given the results of the activation inventory calculations with the isotopically-tailored new structural materials, there is no need for significant limitation concerning divertor or first-wall activation products, or activated corrosion products.

4. ARC Safety Assessment: starting from ITER

ARC is a demonstration fusion power reactor, while ITER is not designed to produce electricity, nevertheless we feel appropriate starting from ITER safety assessments [3][4]. for a preliminary evaluation of ARC safety. ITER and ARC are projects going to be built in the near future, and whose characteristics and components are well detailed. The power plant studies based on the extrapolation of ITER technology (DEMO, PPCS, etc.) deal with designs put too far in the future, and with too many unknown technological questions to be taken as a reference in the present evaluation.

ITER safety assessments have been extensively carried out in the past decades, successfully fulfilling all the requirements for its construction in the Cadarache site in France: its safety evaluations, licensing path and lessons learnt until now, can constitute a good starting basis for some preliminary ARC safety assessments. The planned ARC localization will be in the US, and not in Europe, but some studies dealing with the licensing of former ITER versions in the US are available too [15]. Experience from the FIRE and ARIES studies is available as well [16][17].

A first comparison can be carried out considering the main radiological hazards in the two fusion reactors:

1. Tritium used as fuel for the fusion reaction. In ITER, the inventory of tritium is approximately 4 kg distributed equally in the long term storage, the tritium building, the Tokamak and the hot cells and radwaste facility; considering our estimate of around 0.45 kg (mean value from the best-case scenario) of recirculating tritium in the ARC tokamak, this leads to assess the tritium inventory in ARC to be around 45% that in ITER, that is, around 1.8 kg. Although tritium retention has not been taken into account in this work, a less-than-one-tritium-kilogram fusion power reactor, for the recirculating inventory, could

be a major advance in radiological safety of such reactors.

2. Radiation emitted by activated products, including plasma facing components, vacuum vessel structures, and loose contamination from activated dust generated in the vacuum vessel, potentially leading to inhalation of radioactive materials. Being ARC equipped with a self-cooled breeding blanket, the safety-relevant questions of activated corrosion products generated in the cooling loops by water, and activation of the inner wall of cooling water pipes, potentially leading to external irradiation, can be excluded from ARC safety analysis. A comparison of starting radioactive inventories and environmental source terms at shutdown, reveals that ARC – thanks to the adoption of low-activation materials and a safety-oriented design – presents a radioactive inventory around 20% that of ITER at shutdown, and a biological hazard potential, roughly summarized by the total inhalation dose in Sv, around 10% that of ITER.

In order to study the potential consequences of postulated accident sequences, a set of "Reference Events" has to be defined, chosen to cover all the main hazards foreseen in the ARC design, dealing with all significant inventories of radioactive material, and all initiator event types that have the potential to cause releases. This "deterministic" selection of events has to be paralleled by comprehensive Failure Modes and Effects Analyses (FMEA) of all important ARC systems, analogue to the one which was performed at the component-level for ITER, wherever the design was sufficiently detailed [3][4].

Safety studies for ARC must provide comprehensive lists of Postulated Initiating Events (PIEs), indicating all off-normal occurrences that may have a safety impact: it will have to be verified that, for each PIE, the potential consequences of event sequences that could be initiated are enveloped by those of one of the Reference Events.

The Reference Events cover the major systems, the radioactive inventories distributed amongst these systems and the initiator types that have the potential to cause releases. Examining the main six accidents that are described in ITER safety studies [3][4]:

A. Loss of off-site power

B. In-vessel first wall (FW) pipe break

C. Heat exchanger (HX) leakage

D. Pump trip in divertor

E. Loss of heat divertor sink

F. Tritium process line leakage

We see that some of them are not directly applicable to ARC, such as B: many events dealing with ITER safety analysis have been grouped around the cooling water systems, which are one of the key issues whose safety had to be demonstrated for ITER.

All these events originate from, or imply soon after, a plasma disruption. In general, the plasma behaviour has to be carefully addressed, to show the limited effects of loss of plasma control or exceptional plasma behaviour.

Loss of power has to be investigated to determine if there are requirements for the supply of emergency power. In addition, it can be postulated as a worsening conservative occurrence during certain other accidental sequences

Safety of the tritium plant, with its significant (even if much lower than ITER) inventory has to be addressed too.

Magnet system structural integrity and the potential consequences of arcs are to be dealt with too, mainly due to potential damage to the reactor.

Air ingress into the vacuum vessel and cryostat under various off-normal plant conditions has been investigated, while water ingress does not apply to ARC. For ITER, for instance, a loss of vacuum in the vacuum vessel during plasma operation was identified as one of the main accidents. Although vacuum vessel penetrations are designed with care to provide two confinement barriers, the large number of these penetrations suggests that failure of a penetration line should be investigated to demonstrate the tolerance of the design to such failures. Air ingress into the plasma chamber terminates the plasma with a disruption. Loss of off-site power was also assumed to coincide with the initiating event and last one hour. The vacuum vessel and room pressures equalise about 25 minutes after event initiation. The air in the vacuum vessel heats up but stays below 200°C following the event. Chemical reactions do not occur due to the limited temperatures. In-vessel tritium and dust are mobilised by the air ingress, and some of them are transported to the vacuum vessel pressure suppression system. No mobilised radioactivity is transported out of the vacuum vessel due to the operation of venting systems, which pump out the air in vacuum vessel through the normal vent detritiation system to prevent a back flow. Environmental releases (0.55 g HTO and 0.53 g W-dust) are below project release guideline for Accidents by a factor of eight. They consist in one of the worst-case scenarios for accidental release in ITER after an accident.

A similar evaluation has been carried out for ARC. Preliminary assessments lead to scenarios in which less than 0.5 g of Tritium in the HTO form are released in the worst-case scenario. This turns out to be, according to our evaluations, the envelope accidental release for the ARC reactor.

5. Environmental release envelope scenarios

Following the above considerations, a preliminary environmental impact assessment has been carried out, by means of the RESRAD population dose code [18].

Since no results from the safety analyses in the form of environmental source terms is available yet, the assessment has been carried out simulating the release of given unit quantities of relevant radionuclides in a generic US site. We chose it to have the average characteristics of the Oak Ridge site in Tennessee, one of the three sites of the Manhattan Project. The release is in atmosphere, at the height of 10 meters. The MEI (Most Exposed Individual) turns out in this case to be a small group of persons living downwind at about 1.5 km from the site.

Figure 2 gives the Effective Dose Equivalent (EDE) to the MEI for a unit release of 1 Ci = 3.7 10^{10} Bq of some reference nucides. EDEs are given in Rem (1 Rem = 0.01 Sv). The only relevant nuclide for ARC, given the low-activation characteristics of its structural materials, appears to the Tritium

If we translate data in Figure 2 in international units, we have that Tritium gives a value of 1.24 10^{-6} mSv of EDE per 1 GBq of released activity, by far the lowest value among the examined nuclides (it is, for instance, around 2600 times lower than Cs-137). All the Tritium dose is deriving from internal (in particular, inhalation) exposure.

Given that Tritium's specific activity is 9,650 Curies per gram (3.57×10^{14} Bq/g), this translates in an EDE of around 0.44 mSv per gram of released tritium in non-oxidized form.

We can finally compute a maximum releasable radioactive quantity of tritium, in order to comply with the dose limits we set before as ARC safety goals (see section 3). We have that, for normal operation, a maximum releasable quantity below 2 grams would guarantee to comply with the limits, and the same 2 grams per event in case of incidents. As far as accidents are concerned, a maximum release value is set to 20 grams of Tritium in non-oxidized form and 2 grams in the oxidized form.

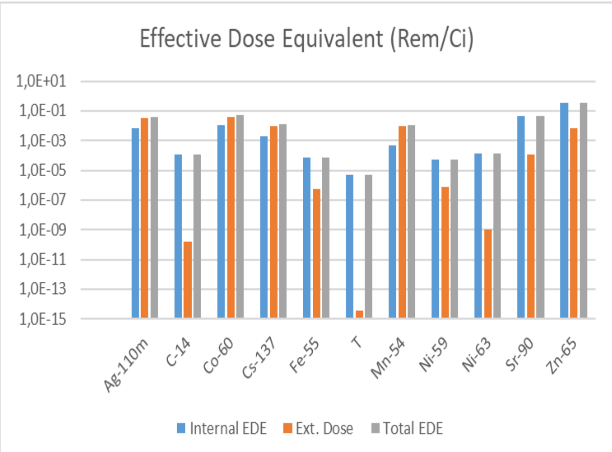

Figure 2 – Effective Dose Equivalent (EDE) to the MEI (Most Exposed Individual) for a unit release of 1 Ci = 3.7 10^{10} Bq. 1 Rem = 0.01 Sv

6. Conclusions

Worst-case accidental release scenarios for ARC, preliminarily derived from the extension to ARC of ITER safety assessments, postulate a release of less than 0.5 g of T in oxidized form as a maximum envelope release quantity.

With a Tritium inventory around 45% that of ITER, we in fact expect that ARC would easily obtain equal or lower values of the maximum credible release in case of the worst conceivable accident.

This quantity would cause a maximum EDE to the MEI around 2.5 mSv once in life. Practically, a value comparable to the annual background radiation dose to a US citizen, with such a frequency as to be not expected to happen during the entire machine lifetime, that is, less than once per century. Such doses do not require the implementation of any evacuation or sheltering of population living around the site, nor any limitation on food consumption.

Collective doses deriving from such postulated events are of low significance, and they all bring to the result that no, i.e. zero, excess cases of neoplastic disease insurgencies are expected. Radiation risk is negligible.

The final response to our safety questions has - of course - to be given after the completion of the ongoing safety analyses for ARC.

Nevertheless, it is reasonable to suppose that the much lower inventories (both in tritium and activation products) of ARC, compared with ITER, its reduced biological hazard potential, and safety-oriented design with a simplified blanket and demountable magnets, should lead ARC to obtain – at least – a safety performance comparable to the excellent one shown by ITER assessments.

Such results would easily permit the siting and licensing of ARC in the US according to that nation's federal regulations.

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