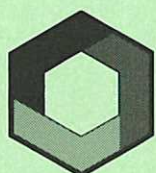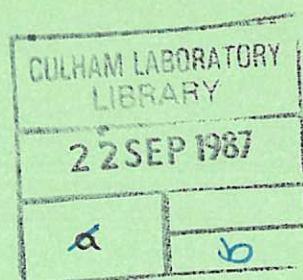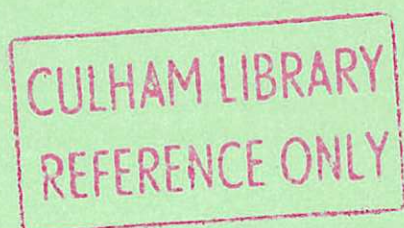# On the Radiological Behaviour of First Wall Fusion Structural Materials

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ABSTRACT

The present report examines the radiological behaviour of low-activity structural materials for the first wall and blanket of nuclear fusion reactors. In this context the allowable concentration limits for all the stable elements are discussed for the neutron irradiation conditions of commercial fusion reactors. Some long-term activation properties of low-activity alloys proposed as structural materials are determined and methods of reducing their residual radiological hazard are examined. The way in which the accuracy of the results depends on the completeness and the uncertainty associated with the neutron cross-section data is discussed and some examples are given of relatively poorly-defined reaction cross-sections the values of which could have important implications for the conclusions.

1. Introduction

Minimisation of the residual radioactive waste could be very important for the public acceptance of fusion energy and should be one of the main goals of the fusion programme. Relative to fission, fusion has the advantage that the thermonuclear reactions do not intrinsically lead to the generation of radioactive products but only to induced radioactivity in the structural and blanket materials, which have a passive role from the standpoint of energy production. While tritium will be required as a fuel for the first generation of commercial fusion reactors, the development of more advanced reactors based on non-radioactive fuels such as D-D or even D-He^3 [1], must be the final aim of fusion research and consequently the limitations implied by the use of tritium should not be seen as an inherent obstacle.

It is in principle possible to select the structural and blanket materials in order to minimise the problems associated with the induced radioactivity. In practice there are several possible sets of requirements which could be imposed and it may not be possible to satisfy all of them simultaneously. Neglecting the engineering requirements on the materials, which are not examined in this paper, there are at least four different areas of operation in which the radiological consequences of the materials selection need to be considered [2]:

1) reactor maintenance and the associated occupational exposure,

2) accident scenario with associated occupational and public exposure,

3) reprocessing and recycling of materials with associated occupational exposure,

4) waste disposal with associated potential public exposure.

Safety requirements in each area have different implications for materials selection and can depend both on the activation and physical properties of the material in question.

The activation properties of a material can be mainly defined through the use of five hazard indices:

a) The specific radioactivity (Bqkg^{-1}), which indicates for a given quantity of material the number of nuclides disintegrating per second and from which all the other indices can be determined through the use of appropriate coefficients. This index does not provide by itself a direct indication of the radiological hazard.

b) The contact, or surface, γ-dose rate (Svh^{-1}), which depends on the intensity and the energy of gamma rays emanating from an active material and thus is a measure of the direct dose received from the material by people in contact with it or standing in its vicinity.

The resulting value depends on the dimensions and shape of the component considered.

c)   The biological hazard potential for ingestion (ALI kg^{-1}) which gives a measure of the dose received from the material when it is ingested through drink or food.

d)   The biological hazard potential for inhalation (ALI kg^{-1}) which gives a measure of the dose received from the material when it is inhaled in the form of dust or gaseous compounds.

e)   The afterheat (Wkg^{-1}) which indicates the rate of heat deposition in the material resulting from radioactive decay and from which it is possible to determine the temperature rise in the component after shutdown.

The total dose equivalent received by each exposed individual has to be maintained below the maximum dose safely acceptable for the human body. The present rule, accepted in most countries but now under review, limits the total occupational exposure to a maximum dose of $50mSvy^{-1}$ and the total exposure of a member of the public to $5mSvy^{-1}$. From the above five indices it is possible to calculate the contribution to the total exposure associated with each material and to determine which precautions have to be taken in regard to shielding and containment. Conversely, the limit on the total exposure imposes conditions on the acceptable value of each index and, depending on whether maintenance, accident or long-term processes are considered, the implications can be very different. The present paper mainly examines the effects on the choice of the reactor materials following from the restriction imposed on the contact γ-dose rate of materials employed in a commercial fusion reactor.

2.   Timescale for safety requirements

Since each of the above indices is strongly dependent on the time after the cessation of irradiation, in order to establish their relative importance in any particular context, the appropriate decay time must be determined.

The relative importance of the different hazard indices varies according to which safety aspect is addressed. Considering the four areas given in section 1 the major trends are as follows:

1)   The requirements for reactor maintenance are mainly dictated by economic considerations, which require that the downtime of the reactor must be minimised. Although remote maintenance will be used for most operations, some occasional direct repairs of items outside the shielding could be necessary, restricting the acceptable cooling time to only a few days. The need for replacement or repair of components removed from the reactor suggests that materials whose activity significantly decays in a timescale of the order of a year would be advantageous. Contamination of the coolant system by eroded

or corroded activated material also contributes to the total occupational exposure, considering that its maintenance should be possible after a few days cooling time. The indices of greatest importance in these operations are the contact dose and, for volatile elements, the inhalation hazard.

2) The accident scenario can be very different from case to case. Consequently, all hazard indices and virtually all timescales may be relevant in this area. Starting from the least dramatic but most probable case of a loss of coolant in the first wall, in which a low afterheat value after a few minutes would be required in order to avoid further damage, all other parameters become involved as the gravity of the accident increases. In the case of a release of activated material outside the reactor building both direct and indirect exposure (air, drink, food) in the short, medium, and long term could have serious implications for the biosphere and the surrounding habitat. As the recent Chernobyl accident has shown, for most sections of the public after a few weeks the ingestion hazard of particular elements becomes the most serious threat because the dilution effect of the atmosphere is less effective in this case.

3) In a recent study [3], the possibility of recycling activated scrap steel material has been related to the surface γ-dose rate alone. Economic reasons will probably require that acceptable conditions for recycling must be reached within a human lifetime at the most.

4) The problem raised by waste disposal depends on the mode of disposal envisaged but the long term decay characteristics for times greater than a hundred years are the most relevant. The need for relatively safe handling of the residual material involves an upper limit of the surface dose rate. In other cases, as for shallow land burial or deep geological disposal options, limitations on the ingestion hazard for particular isotopes present are required.

Of course, if the requirements which follow from 1) and 2) could be satisfied, then most of those in 3) and 4) would also be satisfied. This leads to the 'Inherently Safe Reactor' approach [4] for which advanced structural materials such as ceramics have to be used though developments in this field are very slow and difficult and no practical results have yet been achieved.

In the meantime more limited strategies aimed at improving the acceptability of materials under the requirements 3) and 4) have been developed [5,6] and these are discussed in the following sections.

3.   Blanket model

In previous similar studies [7] activation calculations have been based on the neutron spectrum appropriate to the First Wall (FW) position in the Culham Conceptual Tokamak Reactor Mark II [8]. More recent neutronics

calculations, however, have shown that the blanket configuration of this reactor design is not particularly favourable in terms of tritium breeding. In order to achieve self-sufficiency in tritium supply, a blanket must be designed for near-optimum breeding and in this case the total neutron multiplication and the effective thickness of the blanket would be higher. Consequently, the low-energy components of the FW neutron flux are increased by several orders of magnitude because of the greater number of neutrons back-scattered to the first wall. This increased flux has an important effect through particular reactions which have significant nuclear cross-sections at low energies.

The FW neutron spectra considered in the present study correspond to the blankets designed for self-sufficiency in tritium. In particular, the cases of two major blanket candidates for a DEMOnstration reactor (DEMO) are compared, one referring to a lithium-lead breeder, water-cooled blanket (liquid breeder blanket) with a stainless steel-liquid metal first wall [9], the other referring to a beryllium-lithium ceramic, helium-cooled blanket (solid breeder blanket) with a copper-tungsten first wall [10]. Materials compositions and dimensions are given in Fig. 1, while the corresponding first wall neutron spectra are given in Fig. 2. In the case of the solid breeder blanket the total flux is higher because of the higher multiplication and back-scattering effect of beryllium compared to the lead-water system and this affects mainly the intermediate energy neutron fluxes. The 14MeV peak is similar, while at thermal energy the neutron flux is slightly higher in the liquid blanket case because of the thicker first wall.

The neutron wall loading for the DEMO reactor was taken as $2.6MWm^{-2}$, and the fluxes have been determined with the ANISN transport code [11] in P_3, S_8 approximation and in one dimensional cylindrical geometry for the outer blanket configuration. In the present work the wall loading has been increased to $5MWm^{-2}$ in order to more closely represent the operational conditions expected in a commercial reactor. The irradiation time has been assumed to be 2.5 years of continuous operation, chosen because of the need for periodic replacement of first wall and blanket, giving a total neutron fluence of $12.5MWym^{-2}$.

4. Data library and method of activation calculation

The activation calculations have been performed with an extended version of the isotope depletion code ORIGEN [12], using neutron activation cross-sections contained in an extended version of the UKCTRIIIA data library [13]. The original version of the library contains cross-section data for almost 1500 reactions in elements forming the constituents of materials traditionally used in the nuclear industry. In a recent study [14] it has been extended by the addition of cross-sections for the production of long-lived radioisotopes originating from impurity elements, such as the rare earths. For the purposes of this study a further addition of cross-section data for osmium and of the branching ratio value for the production of ^{178m}Hf has been made.

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A library giving details of the number and the energy of gamma rays emitted per decay event is also required for estimates of the contact dose. All gamma rays with energy below 200keV have been neglected on the grounds that low-energy gamma rays, as well as X-rays and α and β particles, can be easily screened with a relatively thin shield, whereas hard γ-rays would require an unreasonably thick shielding. Nevertheless, the threshold value of 200keV has been chosen largely for computational convenience and an assessment of this assumption will be required at some later stage.

The surface γ-dose rates computed by ORIGEN are those pertaining to an infinite, thick sheet of material, though they also apply with negligible error to a relatively small area, say 1m x 1m, of a plate only a few centimetres thick.

5. <u>Activity and surface γ-dose rate calculations</u>

For considerations of waste management the medium and long term activation properties are of greatest importance. Consequently, data for 50 and 100 years cooling time give a good characterisation of the material behaviour. As noted earlier, the most highly-activated waste comes from the first wall and blanket materials, in particular the structural materials which, because they have also to satisfy a number of engineering requirements, tend to contain radiologically-undesirable elements. Consequently the most critical problem arises from the first wall materials, which are subjected to the highest neutron fluence. For this reason all the following results refer to FW irradiation conditions.

Calculations have been performed for all the stable elements in order to determine their induced activity and surface dose rate when 1ppm by mass is assumed to be present in a non-active matrix of iron. Iron has been chosen because it is a good representation of steels and of other metallic alloys, such as those based on vanadium, with a similar mean atomic number. The presence of the iron matrix has some effects when calculating the surface dose rate because the penetration of γ-rays depends on the nuclear charge and the density of the surrounding material. From these results it is possible to scale the activity and dose rate corresponding to other concentrations and to add the contributions from the individual constituent elements, provided that mass percentages are considered.

Because most of the chemical elements present can be regarded as impurities in a given structural material, the effect of 1ppm of an element gives an immediate indication of its relative acceptability. Tables I and II give the results obtained for activity and surface γ-dose rate respectively. Values are given for 50 and 100 years cooling time and a comparison is made between the solid breeder blanket and the liquid breeder blanket cases. The isotopes that give the most important contributions to the total, down to 1%, are also indicated. Values of $0.1 Bqkg^{-1}$ for the activity and $10^{-12} Svh^{-1}$ for the surface dose rate have been taken as the minimum values of interest.

The results obtained for the case of the liquid breeder blanket are in general within a factor 2 of the corresponding value for the solid breeder blanket. This shows that when blankets with self-sufficient tritium production are considered, the activation of the structural materials is not strongly sensitive to the blanket design, so that for further discussion only the values referring to the solid blanket case are considered.

The activity results are important as a general indication of the radiological behaviour and as a way of classifying waste materials. According to the EEC regulations all materials exceeding the activity level of $10^5 Bqkg^{-1}$ after an appropriate storage time (which can be up to a maximum of 100 years) must be disposed of in a Final Repository (FR) [22]. Among the various types of FR, the Shallow Land Burial (SLB) is the cheapest and most attractive one. It is defined as a near-surface underground repository (at least 5m deep) provided with natural or engineered barriers to prevent intrusion for at least 500 years. If permanent disposal cannot be avoided, the fusion waste should preferably be acceptable for SLB. The limiting activity level for SLB is different for each radioactive isotope depending on its biological and nuclear characteristics but, as a general rule, according to the present UK regulations [23], wastes should contain less than $12 MBqkg^{-1}$ beta or gamma activity or less than $4 MBqkg^{-1}$ alpha activity in order to be eligible for shallow land burial. The values given in Table I show that some elements, even in concentration as low as 1ppm and after 100y cooling time, do not satisfy such a requirement and suggest that a detailed analysis will be necessary in order to assess the problem.

The surface dose rate levels given in Table II have important implications for the possibility of handling and reprocessing the scrap materials and this aspect will be discussed in the following section.

6.   Surface γ-dose rate criteria and implications

In this section the possibility of reprocessing the scrap material is considered as an alternative to permanent disposal. A recent feasibility study by the British Steel Corporation [3] has concluded that active steel could be remelted and converted at least to a tube product, provided that its surface dose rate does not greatly exceed $0.01 Svh^{-1}$ and that this could be accomplished using only well-established steelmaking and processing techniques and radiological protection practices. It is envisaged that this recycling process would return the still active reclaimed material in the form of new components to subsequent generations of reactors, thus conserving structural material and avoiding the need to dispose of large quantities of radioactive waste.

There would be strong economic incentives for recycling after the shortest practicable cooling time and the limitations on the permissible concentrations of the chemical elements imposed by the requirement that the contact dose rate of the material does not exceed $0.01 Svh^{-1}$ after 50y

cooling time have been evaluated using the values given in Table II and assuming that the same dose rate limit can be applied to the recycling of materials other than steels. Table III shows the range of allowed concentrations for each element following adoption of such a criterion, and includes for comparison the values corresponding to the more restrictive 'hands-on' criterion, which requires that a surface dose rate lower than 2.5×10^{-5} Svh^{-1} be attained after 100y cooling time.

In the case of the 'recycling' limit it is seen that, despite the presence of some elements such as Eu, Co, Ag, Tb, and Ir which are permissible only at very low concentrations, all elements are allowed at levels that are probably acceptable from the point of view of the degree of purity attainable in industrial production. This is suggested by Table VI where the lowest concentrations of residual elements believed to be achievable by current production methods for steel are given [24]. The limits required by the 'hands-on' criterion may be too low for any practical feasibility in the near future.

As shown in previous studies [6,14] the long term surface dose rate is always dominated by isotopes generated from impurity elements, thus indicating that in the development of 'low-activity' materials a major effort is required to find new techniques for achieving higher degrees of purity.

7. Bremsstrahlung corrections

The electrons emitted in some β-decays could produce bremsstrahlung γ-rays when they cross the electric field within the atoms. If the energy of the γ-rays is greater than 200keV then they can give an additional contribution to the surface γ-dose rates given in Table II and described in the previous section. A formula that permits calculation of the additional surface γ-dose rate associated with electron bremsstrahlung radiation is given in [14], where the case of the β-emitter isotope ^{186m}Re is considered. As a consequence, the allowed mass percentage for rhenium under the 'hands-on' criterion after 100y cooling time decreases from 1.1% to 680ppm.

In general, however, the bremsstrahlung contribution is not appreciable and only for 3 other long-lived isotopes has it been found significant: ^{36}Cl, ^{39}Ar, and ^{121m}Sn. Consequently, when the above 'hands-on' criterion is applied to the elements producing these isotopes under neutron irradiation, the value of their allowed mass concentration in first wall materials decreases. In particular, for Cl the value decreases from 44% to 30ppm, for Ar from 100% to 27ppm, for K for 47% to 30ppm, for Ca from 4.5% to 0.4%, and for Sn from 14% to 0.6%.

8. Examples of low-activity materials

The activity and the surface dose rate vs. cooling time for several alloys
have been calculated within the conditions described in sections 3 and 4,
and these are presented in the graphs of Figs.3-14. In such graphs, the
principal isotopes contributing to the total value are indicated by dots.
The convention used is that the ordinate of each dot represents the
contribution of the corresponding isotope at shutdown and the abcissa its
half-life.

For reference, two standard stainless steels are considered, the austenitic
steel AISI-316 and the martensitic steel FV448. Some low-activity variants
of these steels known respectively as OPTSTAB and LA7 [20,21], the
compositions of which are given in Table V, are considered both in their
pure form and with a likely range of impurities included (see Table VI).
More advanced low-activity materials, such as vanadium alloys and silicon
carbide (SiC) are also considered. The ceramic SiC contains 70% by weight
of Si while, as examples of vanadium alloys, the following three
compositions have been examined: a) V-22(wt%)Ta, b) V-15Cr-8.5W, c)
V-15Cr-5Ti. In these cases, only calculations for pure materials have been
performed because no evaluation of their probable impurity contents have
yet been made, although all indications are that they could be manufactured
to much higher purity specifications than those assumed for the steels.

The concept of low-activity steels is based on the possibility of
substituting the radiologically-undesirable elements in conventional steels
with others more acceptable, while maintaining at least equivalent
engineering properties.

In the case of vanadium alloys a completely new technology is needed,
trying to improve each desirable property with minor additions of
appropriate elements to pure vanadium, which has low long-term activity.
The main technical problem is the readiness with which they react with
non-metallic elements such as oxygen, carbon and nitrogen and the
deleterious consequences of this interaction. Such a problem makes the
V-alloys attractive only when used in compatible environments, in
particular in combination with lithium or lithium-lead breeder materials in
helium-cooled or self-cooled blankets [6].

Silicon carbide in fibre-reinforced form is said to be one of the most
promising ceramic structural materials [6], particularly from the point of
view of fracture behaviour and failure mode which are typical problems for
other ceramics. It is an example of a material showing a very low activity
level even after a cooling time of a few hours (Fig.14-A). On the other
hand Fig.14-B shows that the very long-term γ-dose rate is relatively high,
just below the 'hands-on' criterion limit. The major problem is that a
sufficient engineering base does not yet exist.

In the literature some aluminium alloys are also considered as
low-activation materials [16]. In fact, as can be seen from the criteria
presented in Table III, aluminium does not appear to be an acceptable base

material for low-activity alloys. This discrepancy reveals a possible uncertainty in the corresponding nuclear data that will be discussed in section 10. On the other hand, the limited maximum temperature of about 125°C at which these types of alloys can be used [6] precludes any possible interest in using such materials for commercial reactors.

With the exception of the advanced SiC ceramic, all of the low-activity materials considered here show a significant advantage compared to conventional steel only for long cooling times, typically after a few tens of years after shutdown, which is the region of interest for recycling and waste management strategies. In this respect vanadium alloys offer greater advantages than low-activity steels. On the other hand, they show no particular improvement for short term activation associated with maintenance and safety problems. Moreover, even the long-term benefits could be lost if the impurity contents cannot be controlled in accordance with the limits indicated in Table III.

Finally, it should be noted that the first wall material receives the highest neutron fluence of all reactor components. Economic factors could suggest different strategies for active scrap FW materials and for those produced in the blanket and in the shielding. Low-activity materials which do not offer great advantage when used in the first wall could represent a significant saving when used in the blanket or in the shielding which in fact involve a much greater amount of structural material compared to the first wall.

9. Isotopic tailoring considerations

Isotopic tailoring can be applied to those elements naturally occurring in two or more isotopical states, in order to separate the isotopes mainly responsible for the production of troublesome radioisotopes under neutron irradiation. Depending on the objectives, however, different isotopes might need to be removed.

Consider the important, although somewhat hypothetical examples of pure low-activity steels LA7 and OPTSTAB. The objective of satisfying the 'recycling' criterion, that requires the surface γ-dose rate remaining below $0.01 Svh^{-1}$, is reached after a cooling time of about 70 years (Figs. 6-B, 8-B), mainly governed by the presence of ^{60}Co produced from iron [17]. By isotopic selection of the iron component, whose isotopical abundances are given in Table VII, and using only the species ^{54}Fe and ^{56}Fe, it is possible to decrease the cooling time to only about 30 years.

If several utilisation cycles are considered consisting, for example, of 2y operation and 30y cooling time, then only ^{54}Fe is acceptable because the use of ^{56}Fe leads to the buildup of an unacceptable amount of ^{60}Co after only 3 cycles. If a longer cooling time is allowed in each cycle, however, a greater number of cycles without reaching the $0.01 Svh^{-1}$ dose rate limit becomes possible even with the use of ^{56}Fe. For example, 10 cycles are possible if the cooling time is extended to 50y.

Since no separation process can be expected to be totally effective, it is not possible to prepare pure monoisotopic iron and it is therefore useful to determine some limits of acceptability for the residual iron isotopes. Table VII shows the allowed abundance for each Fe-isotope, when 5 cycles of 2y operation and 50y cooling time are considered within the 'recycling' criterion restrictions.

On the other hand, the presence of impurities overshadows the advantage of isotopic tailoring because their contribution to the total surface dose rate is already noticeable after 30y cooling time and becomes dominant for longer times (Figs.7-B and 9-B). In fact, when the mixture of impurities given in Table VI is included in the composition, the low-activity steels satisfy the recycling requirement only after 90y cooling time. Nevertheless it is reasonable to suppose that the process of isotope separation would itself greatly reduce the impurity content associated with the isotopically-separated element. This assumption leads to the graph shown in Fig.10-B which corresponds to the results obtained for the LA7 steel with iron in the form ^{54}Fe and only 15% of the previous impurity content, corresponding to a tentative estimate of the residual element content introduced via the alloy components other than the iron. Under this assumption, recycling becomes possible after about 60 years, showing that the impurities still have a dominant effect with a consequent reduction in the advantages offered by the isotopic tailoring of iron.

Certain elements previously regarded as undesirable under the 'recycling' requirements, such as Mo, Ni, Ti and Pb, could be used in small relative concentrations by means of isotopic tailoring. Limitations on their isotopic abundances are given in Table VII for only one cycle consisting of 2y operation and 50y cooling time, and taking into account the typical percentage with which they appear in alloys. The restrictions implied by the 'hands-on' criterion after 100y cooling time are also given for comparison. When the sum of the allowed isotopic abundances is lower than 100% it is understood that no isotope can fulfil that requirement.

If one considers the potential of isotopic tailoring with the objective of reducing the short-term activity and biological hazard potentials for up to a few months after irradiation of the low-activity alloys the outcome would be considerably different. For instance, the preferred isotope for iron would be ^{57}Fe, which would reduce the activity by about 2 orders of magnitude, ^{61}Ni for nickel, ^{100}Mo for molybdenum, ^{54}Cr for chromium, and ^{50}Ti for titanium.

On the other hand, the selection of isotopes on the basis of very long term specific radioactivity, eg. when considering permanent disposal strategies, could lead to quite different conclusions. For instance, in the case of iron, the species ^{54}Fe, which has previously been selected under the 'recycling' criterion, shows in fact the highest very long term activity at several hundreds of years because of the high production of the long-lived ^{53}Mn, the activity of which is not associated with any significant surface γ-dose rate.

Detailed considerations of the last two subjects are beyond the scope of the present study but they have demonstrated the difficulty of improving simultaneously all the activation characteristics of a material.

10. Comparison with other results

The 'hands-on' dose rate criterion for 100y cooling time has been applied by other authors in previous studies. In Table IV are given some of those results in terms of the allowed concentration of each element together with the limits found in the present study. A comparison between the different sets of data shows that in some cases there is a significant disagreement.

Jarvis [7,8] has performed calculations for most elements using the UKCTRIIIA library, extended with only some 14MeV cross-sections for impurity elements and using the neutron flux pertaining to CCTRMkII reactor, which has a greatly reduced low-energy component compared to the flux used in the present study, and assuming a fluence of $20MWym^{-2}$. The surface γ-dose rate is, in fact, determined in a different way, considering each element present as impurity in a matrix of the element itself. Significant differences have been found between the published data which, in the case of the Jarvis estimates, tend to be optimistic for some elements, namely Fe, Co, Ni, Cu, Pd, Gd, Ho, Yb, Lu, Hf, Ta, W, Os and Pb.

Ponti [15] has performed calculations using REAC-ECN, a new activation library, more complete than UKCTRIIIA, that contains the most recent cross-section evaluations and assuming a fluence of $10MWym^{-2}$. In this case, the surface γ-dose rates contain also the dose due to low-energy gammas, with the lower limit of 10 keV compared to the 200 keV adopted in the present study. The major differences between these published results and those given in the present study concern Sc, Ti, Fe, Sr, In, Sn, Sb, Te, Xe, Lu, Hf, Ta, W, and Pb. Particularly important are the greater allowed percentage for Ti and the lower percentages for Ta and W, which mainly derives from the differences in the cross-section data, as will be discussed in the following section. In fact these elements are being used in the composition of some low-activity materials given in section 8, and a change in their activation characteristics could substantially modify the strategy for development of such materials.

A special consideration is required for Fe, for which in the present study a maximum allowed concentration of 19% has been found in the case of the solid breeder blanket, and of 34% in the liquid breeder blanket case. Such a difference shows the particular sensitivity to the neutron flux and spectrum of the induced surface dose rate in iron, associated with the decay of ^{60}Co produced through successive (n, γ) reactions. In both the Jarvis and Ponti results, Fe is allowed without restrictions. In the case of the Jarvis calculations the difference is a consequence of the different neutron spectrum used, while in the Ponti calculations the lower fluence considered and possible differences in the cross-section values employed also have some importance.

11. Discussion of cross-section data uncertainty

The objective in this section is to discuss some particular topics relevant to the present efforts devoted to improvement of the data library. The original UKCTRIIIA neutron activation library contained data only for the basic elements to be used in fusion reactors. The uncertainty in the data varied according to their origin, in particular, whether they were derived from theoretical model calculations or from experiments and, in the case of experiments, how reliable the measurements are.

With the dependence on the neutron energy as an additional factor, the range of uncertainty is very wide. At one end of the scale, the most frequently measured, and therefore most accurate, cross-sections are probably known to better than 10%. In the middle region are those reactions for which there are some data (generally at ~ 14MeV) but for which model calculations have to be used to provide values over the full energy range required. In these cases, the cross-sections may typically be accurate to 15-30%. At the extreme, there are many instances for which there are no measurements and theory must be employed. For these, the uncertainty depends very much on the model used for the calculation and the type of reaction being considered. Good model codes may be capable of giving results to 30% for dominant cross-sections well above threshold but, for small cross-sections or ones close to the threshold, the uncertainties can be much higher and, in extreme cases (eg. estimation of cross-sections to isomeric states), could be an order of magnitude or more.

Nevertheless, the first concern has been to solve the problem of the omissions of some important cross-section data, leaving to a later stage the improvement of existing values. In a recently published work [14] new data have been generated with a theoretical code THRES-F [19] in order to fill some gaps in the library, mainly those concerning impurity elements.

Several other problems have yet to be addressed: a) the impurity element cross-sections recently added to the library include only reactions leading to the production of radionuclides having half lives greater than 5y; b) some chain reactions leading to long-lived isotopes, which can be important when high neutron fluences are considered, have intermediate steps missing; c) some cross-sections derived from old measurements should be checked against newer available data; d) the branching ratios for some reactions leading to long-lived metastable states are unknown.

Examples of the last two items are: 1) the production from tungsten and tantalum of ^{178m}Hf (31y half-life) that could lead to a significant long term surface dose rate. This production may entirely depend on the ^{179}Hf(n,2n) cross-section branching ratio, which in the present calculations has been assumed to be 5×10^{-3} but which is actually unknown and will require a major experimental effort to be determined; 2) the production from titanium of ^{42}Ar via successive (n,α) and (n,n'α) reactions for which old cross-sections, probably over-estimated, are used; 3) the

production from aluminium of ^{26}Al through the ^{27}Al(n,2n) reaction for which more recent measurements [16] give a lower value than that in UKCTRIIIA.

The first two examples have direct implications for the development of some LA materials described in section 8. If, for instance, the values assumed by Ponti are proved correct, then the use of any significant amount of Ta would be unacceptable, with serious implications for the OPTSTAB steel and the VTa alloy development. On the other hand the use of modest additions of Ti in the vanadium-based alloys would be allowed, with advantages to the properties obtainable. Therefore, it would be desirable to assess the correctness and the reliability of the newly-compiled library and to assemble a joint library taking into account all the new information available. This work is currently under way in the Nuclear Physics Division at UKAEA-Harwell and it will be the next necessary step for improved activation calculations.

12. Conclusions

The present paper reviews the most recent developments in the field of activation calculations for low-activation materials for the first wall of fusion power reactors. In particular, the results of the activation calculations performed for the irradiation of all stable elements, using the neutron cross-section data contained in an extended version of the UKCTRIIIA activation library, have been examined. The consequences of the results for the allowable composition of structural materials have been analysed with particular attention to the long term surface dose rate and the implications for recycling and hands-on processing.

The benefit of elemental substitution and of isotopic tailoring in structural material alloys have also been investigated. In the case of low-activation steels the advantage of their use as FW-material compared to the use of conventional steels is significant when the recycling process and the associated relatively long cooling time is considered.

The advantages of using advanced structural materials, such as vanadium alloys or ceramics, are evident for all cooling times including timescales relevant to accident scenarios, recycling and permanent disposal. However, it is not at all certain at this point whether an appropriate balance of engineering properties as well as favourable activation characteristics can be developed for these classes of materials.

The presence of unintended impurities in low-activity materials is a critical issue. All improvements of the radiological performances of such materials could be nullified if some impurity elements, such as Ag, Eu, Tb, Ho, Ir, Nb, Os and Bi, are not maintained at very low concentrations.

Recent reassessment of the basic nuclear data published in preliminary form in the literature would, if correct, affect our conclusion regarding the radiological properties of LA materials predicted from the UKCTRIIIA data

base and its extension. In particular, the use of Ta as an alloying element would be precluded. Tungsten as well would suffer severe limitations. Some possible improvements to the nuclear data base, such as determination of unknown branching ratios or replacement of old data, have been discussed to give a guideline to further study.

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Table I – Induced activity $(Bqkg^{-1})$ after 2.5y of neutron irradiation at $5MWm^{-2}$ for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTR III A library).

| Element (Z) | 50 years cooling time | | 100 years cooling time | | |
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	main isotope(s) responsible
1-H	–	–	–	–	–
2-He	–	–	–	–	–
3-Li	4.1 E+8*	4.0 E+8	2.4 E+7	2.4 E+7	^3H
4-Be	7.9 E+6	7.1 E+6	4.7 E+5	4.2 E+5	^3H
5-B	1.5 E+7	1.2 E+7	8.9 E+5	7.1 E+5	^3H
6-C	2.3 E+3	1.6 E+3	1.5 E+2	1.1 E+2	^3H
7-N	4.8 E+6	4.1 E+6	9.5 E+5	8.9 E+5	^{14}C, ^3H
8-0	5.5 E+2	4.6 E+2	5.5 E+2	4.6 E+2	^{14}C
9-F	7.3 E+5	6.2 E+5	4.4 E+4	3.7 E+4	^3H
10-Ne	6.3 E+2	3.5 E+2	6.3 E+2	3.5 E+2	^{14}C
11-Na	2.7 E+2	2.2 E+2	6.4	4.5	^3H
12-Mg	2.2 E-1	1.7 E-1	1.6 E-2	1.1 E-2	^3H, ^{26}Al
13-Al	1.0 E+4	8.7 E+3	1.2 E+3	1.0 E+3	^{26}Al, ^3H
14-Si	7.1 E-1	5.2 E-1	–	–	^{26}Al, ^3H
15-P	2.8	2.0	1.7 E-1	1.2 E-1	^3H
16-S	3.8 E+1	2.0 E+1	3.5 E+1	1.8 E+1	^{32}Si (^{32}P)
17-Cl	2.0 E+4	2.4 E+4	1.7 E+4	2.2 E+4	^{36}Cl
18-Ar	1.6 E+7	1.3 E+7	1.4 E+7	1.2 E+7	^{39}Ar
19-K	1.4 E+7	1.1 E+7	1.3 E+7	9.8 E+6	^{39}Ar
20-Ca	1.1 E+5	7.9 E+4	9.1 E+4	6.5 E+4	^{39}Ar

*Read $4.1 \times 10^{+8}$ [-] represents a level below $0.1 Bqkg^{-1}$.

Table I (continued) – Induced activity (Bqkg^{-1}) after 2.5y of neutron irradiation at 5Mwm^{-2} for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library).

Element (Z)	50 years cooling time		100 years cooling time		main isotope(s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
21-Sc	7.1 E+3	5.2 E+3	3.5 E+3	2.4 E+3	^{39}Ar, ^{42}Ar (^{42}K)
22-Ti	1.2 E+3	9.3 E+2	3.8 E+2	2.8 E+2	^{39}Ar, ^{42}Ar (^{42}K)
23-V	1.3 E+3	1.1 E+3	7.7 E+1	6.6 E+1	^{3}H
24-Cr	1.5 E+3	1.3 E+3	9.2 E+1	8.0 E+1	^{3}H
25-Mn	1.4 E+3	1.2 E+3	9.1 E+1	7.9 E+1	^{3}H
26-Fe	3.0 E+3	2.6 E+3	1.7 E+2	1.5 E+2	^{53}Mn, ^{3}H
27-Co	1.2 E+7	9.7 E+6	1.8 E+4	1.5 E+4	^{60}Co, ^{3}H
28-Ni	1.1 E+6	1.1 E+6	7.4 E+5	7.0 E+5	^{63}Ni, ^{59}Ni
29-Cu	5.2 E+6	4.1 E+6	3.5 E+6	2.8 E+6	^{63}Ni
30-Zn	6.2 E+5	5.1 E+5	4.3 E+5	3.5 E+5	^{63}Ni
31-Ga	1.3 E+3	1.1 E+3	2.9 E+2	2.1 E+2	^{63}Ni, ^{3}H
32-Ge	–	–	–	–	–
33-As	–	–	–	–	–
34-Se	5.1 E+4	3.8 E+4	5.1 E+4	3.8 E+4	^{79}Se
35-Br	2.0 E+3	1.5 E+3	1.3 E+3	9.5 E+2	^{79}Se, ^{81}Kr
36-Kr	1.1 E+7	5.6 E+6	4.3 E+5	2.2 E+5	^{85}Kr, ^{81}Kr
37-Rb	8.0 E+4	6.0 E+4	3.1 E+3	2.4 E+3	^{85}Kr, ^{3}H
38-Sr	7.1 E+2	2.5 E+2	2.0 E+2	7.1 E+1	^{90}Sr (^{90}Y)
39-Y	8.6 E+2	7.1 E+2	7.6 E+1	5.6 E+1	^{3}H. ^{90}Sr (^{90}Y)
40-Zr	1.9 E+4	1.6 E+4	6.3 E+3	5.3 E+3	^{90}Sr (^{90}Y), ^{93}Zr, ^{93m}Nb

Table I (continued) - Induced activity (Bqkg^{-1}) after 2.5y of neutron irradiation at 5MWm^{-2} for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library).

Element (Z)	50 years cooling time		100 years cooling time		main isotope(s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
41-Nb	5.7 E+6	4.8 E+6	8.1 E+5	5.9 E+5	^{93m}Nb, ^{94}Nb
42-Mo	1.9 E+5	1.4 E+5	1.9 E+5	1.4 E+5	^{93}Mo, ^{93m}Nb
44-Ru	6.2 E+2	5.4 E+2	2.0 E+2	1.7 E+2	^{99}Tc, ^{3}H, ^{93m}Nb
45-Rh	3.9 E+3	3.4 E+3	5.0 E+1	4.3 E+1	^{3}H, ^{99}Tc
46-Pd	1.9 E+4	1.3 E+4	1.5 E+4	1.0 E+4	^{108m}Ag (^{108}Ag)
47-Ag	1.3 E+7	1.0 E+7	1.0 E+7	7.8 E+6	^{108m}Ag (^{108}Ag)
48-Cd	2.7 E+4	1.3 E+4	2.0 E+4	9.5 E+3	^{108m}Ag (^{108}Ag)
49-In	5.5 E+2	4.7 E+2	3.4 E+1	2.9 E+1	^{3}H, ^{108m}Ag (^{108}Ag)
50-Sn	1.1 E+6	9.7 E+5	7.3 E+5	6.1 E+5	^{121m}Sn
51-Sb	2.3 E+3	1.8 E+3	1.3 E+3	9.3 E+2	^{121m}Sn, ^{3}H
52-Te	1.1 E+2	9.2 E+1	1.0 E+2	8.1 E+1	^{129}I, ^{121m}Sn
53-I	3.6 E+2	3.1 E+2	2.2 E+1	1.9 E+1	^{3}H
54-Xe	7.3 E+4	4.2 E+4	2.3 E+4	1.3 E+4	^{137}Cs, ^{135}Cs
55-Cs	7.7 E+5	6.7 E+5	3.1 E+4	2.7 E+4	^{133}Ba, ^{135}Cs
56-Ba	4.1 E+5	3.6 E+5	2.2 E+4	1.9 E+4	^{133}Ba, ^{137}Cs
57-La	2.5 E+3	1.8 E+3	2.2 E+3	1.6 E+3	^{137}La, ^{3}H
58-Ce	5.2 E+2	4.3 E+2	1.6 E+2	1.3 E+2	^{137}La, ^{3}H
59-Pr	3.7 E+2	3.2 E+2	3.8 E+1	3.3 E+1	^{3}H, ^{137}La
60-Nd	3.8 E+6	2.3 E+6	2.6 E+6	1.6 E+6	^{151}Sm
62-Sm	3.3 E+7	3.3 E+7	2.2 E+7	2.2 E+7	^{151}Sm, ^{145}Pm

Table I (continued) - Induced activity (Bqkg^{-1}) after 2.5y of neutron irradiation at 5MWm^{-2}) for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library).

Element (Z)	50 years cooling time		100 years cooling time		main isotope(s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
63-Eu	2.8 E+8	2.8 E+8	2.0 E+7	1.9 E+7	^{152}Eu, ^{150}Eu, ^{154}Eu, ^{151}Sm
64-Gd	2.8 E+5	2.6 E+5	7.5 E+3	6.7 E+3	^{154}Eu, ^{152}Eu, ^{151}Sm
65-Tb	2.9 E+7	2.4 E+7	2.3 E+7	1.9 E+7	^{158}Tb, ^{157}Tb
66-Dy	1.8 E+5	1.8 E+5	1.4 E+5	1.3 E+5	^{157}Tb, ^{158}Tb
67-Ho	2.9 E+6	2.8 E+6	2.8 E+6	2.7 E+6	^{166m}Ho
68-Er	1.0 E+6	8.9 E+5	3.6 E+5	3.1 E+5	^{163}Ho, ^{166m}Ho
69-Tm	1.5 E+3	1.4 E+3	1.3 E+3	1.2 E+3	^{166m}Ho, ^{3}H
70-Yb	1.4 E+3	1.6 E+3	1.8 E+1	1.4 E+1	^{178m}Hf, ^{3}H
71-Lu	2.3 E+3	2.8 E+3	4.0 E+1	3.3 E+1	^{178m}Hf, ^{3}H
72-Hf	2.8 E+4	2.2 E+4	9.3 E+3	7.3 E+3	^{178m}Hf
73-Ta	6.0 E+2	5.1 E+2	3.3 E+2	2.8 E+2	^{3}H, ^{178m}Hf, ^{182}Ta
74-W	1.2 E+4	1.0 E+4	1.2 E+4	1.0 E+4	^{186m}Re (^{186}Re)
75-Re	1.1 E+5	1.3 E+5	1.1 E+5	1.3 E+5	^{186m}Re (^{186}Re)
76-Os	3.7 E+6	4.1 E+6	3.0 E+6	3.3 E+6	^{192m}Ir (^{192}Ir), ^{193}Pt
77-Ir	2.0 E+7	1.7 E+7	1.6 E+7	1.4 E+7	^{192m}Ir (^{192}Ir), ^{192}Pt
78-Pt	1.4 E+7	1.2 E+7	7.0 E+6	5.9 E+6	^{193}Pt
79-Au	-	-	-	-	-
80-Hg	1.1 E+3	4.7 E+2	-	-	^{204}Tl
81-Tl	1.3 E+5	9.7 E+4	2.8 E+1	2.3 E+1	^{204}Tl, ^{3}H
82-Pb	6.0 E+2	3.7 E+2	1.2 E+2	6.5 E+1	^{207}Bi, ^{209}Po, ^{208}Bi
83-Bi	1.6 E+6	1.1 E+6	5.8 E+5	4.0 E+5	^{207}Bi, ^{209}Po, ^{208}Bi

Table II - Induced surface γ-dose rate (Svh^{-1}) after 2.5y of neutron irradiation at 5MWm^{-2}) for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library).

Element (Z)	50 years cooling time		100 years cooling time		main isotope (s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
1-H	-	-	-	-	-
2-He	-	-	-	-	-
3-Li	-	-	-	-	-
4-Be	-	-	-	-	-
5-B	-	-	-	-	-
6-C	-	-	-	-	-
7-N	-	-	-	-	-
8-O	-	-	-	-	-
9-F	-	-	-	-	-
10-Ne	-	-	-	-	-
11-Na	9.4 E-8*	8.1 E-8	-	-	^{22}Na
12-Mg	2.3 E-11	1.7 E-11	3.4 E-12	2.2 E-12	^{26}Al
13-Al	5.4 E-7	4.7 E-7	5.4 E-7	4.7 E-7	^{26}Al
14-Si	3.5 E-11	2.6 E-11	3.5 E-11	2.6 E-11	^{26}Al
15-P	-	-	-	-	-
16-S	-	-	-	-	-
17-Cl	5.7 E-11	8.0 E-11	5.7 E-11	8.0 E-11	^{36}Cl
18-Ar	-	-	-	-	^{36}Cl
19-K	5.3 E-11	4.3 E-11	5.3 E-11	4.3 E-11	^{40}K, ^{36}Cl
20-Ca	1.1 E-9	9.6 E-10	5.5 E-10	4.5 E-10	^{40}K, ^{42}Ar (^{42}K)

*Read 9.4 x 10^{-8} [-] represents a level below 10^{-12} Svh^{-1}.

Table II (continued) - Induced surface γ-dose rate (Svh^{-1}) after 2.5y of neutron irradiation at 5MWm^{-2} for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library).

Element (Z)	50 years cooling time		100 years cooling time		main isotope(s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
21-Sc	1.0 E-7	6.7 E-8	3.6 E-8	2.3-8	^{42}Ar (^{42}K)
22-Ti	2.7 E-8	1.9 E-8	9.5 E-9	6.6-9	^{42}Ar (^{42}K)
23-V	7.0 E-12	4.1 E-12	2.4 E-12	1.4-12	^{42}Ar (^{42}K)
24-Cr	1.9 E-12	1.2 E-12	-	-	^{42}Ar (^{42}K)
25-Mn	-	-	-	-	-
26-Fe	9.6 E-8	5.3 E-8	1.3 E-10	7.4 E-11	^{60}Co
27-Co	7.4 E-3	6.2 E-3	1.0 E-5	8.5 E-6	^{60}Co
28-Ni	4.3 E-5	3.4 E-5	6.0 E-8	4.8 E-8	^{60}Co
29-Cu	2.4 E-5	2.0 E-5	3.3 E-8	2.7 E-8	^{60}Co
30-Zn	9.8 E-8	7.0 E-8	1.6 E-10	1.1 E-10	^{60}Co
31-Ga	-	-	-	-	-
32-Ge	-	-	-	-	-
33-As	-	-	-	-	-
34-Se	-	-	-	-	-
35-Br	8.9 E-10	5.9 E-10	8 9 E-10	5.9 E-10	^{81}Kr
36-Kr	6.3 E-6	3.3 E-6	2.6 E-7	1.4 E-7	^{85}Kr, ^{81}Kr
37-Rb	4.7 E-8	3.5 E-8	1.8 E-9	1.4 E-9	^{85}Kr
38-Sr	4.5 E-11	1.7 E-11	1.0 E-11	3.6 E-12	^{90}Sr (^{90}Y), ^{85}Kr
39-Y	5.2 E-12	2.8 E-12	1.5 E-12	8.0 E-13	^{90}Sr (^{90}Y)
40-Zr	4.5 E-9	3.4 E-9	3.9 E-9	2.9 E-9	^{94}Nb, ^{90}Sr (^{90}Y)

Table II (continued) - Induced surface γ-dose rate (Svh^{-1}) after 2.5y of neutron irradiation at 5MWm^{-2} for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library).

Element (Z)	50 years cooling time		100 years cooling time		main isotope(s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
41-Nb	1.1 E-4	6.4 E-5	1.1 E-4	6.4 E-5	^{94}Nb
42-Mo	2.1 E-7	1.9 E-7	2.0 E-7	1.9 E-7	^{94}Nb, ^{98}Tc
44-Ru	1.6 E-9	1.4 E-9	1.6 E-9	1.4 E-9	^{98}Tc, ^{94}Nb
45-Rh	2.1 E-6	1.8 E-6	2.8 E-11	2.3 E-11	^{98}Tc, ^{102}Rh
46-Pd	6.4 E-6	4.4 E-6	4.9 E-6	3.3 E-6	^{108m}Ag
47-Ag	4.3 E-3	3.5 E-3	3.3 E-3	2.6 E-3	^{108m}Ag
48-Cd	8.9 E-6	4.2 E-6	6.8 E-6	3.2 E-6	^{108m}Ag
49-In	6.5 E-10	4.9 E-10	4.9 E-10	3.7 E-10	^{108m}Ag
50-Sn	2.9 E-8	1.8 E-8	1.8 E-10	1.3 E-10	^{108m}Ag
51-Sb	–	–	–	–	–
52-Te	5.2 E-10	4.5 E-10	–	–	^{125}Sb
53-I	–	–	–	–	–
54-Xe	8.5 E-6	4.9 E-6	2.7 E-6	1.5 E-6	^{137}Cs
55-Cs	3.2 E-5	2.8 E-5	1.2 E-6	1.0 E-6	^{133}Ba
56-Ba	1.9 E-5	1.7 E-5	1.5 E-6	1.3 E-6	^{137}Cs, ^{133}Ba
57-La	3.8 E-10	2.7 E-10	1.2 E-10	8.4 E-11	^{137}Cs
58-Ce	3.4 E-9	2.9 E-9	1.3 E-10	1.1 E-10	^{133}Ba, ^{137}Cs
59-Pr	–	–	–	–	–
60-Nd	5.7 E-6	3.6 E-6	4.1 E-7	2.5 E-7	^{152}Eu, ^{150}Eu
62-Sm	8.2 E-5	6.7 E-5	4.3 E-6	4.1 E-6	^{152}Eu, ^{154}Eu, ^{150}Eu

Table II (continued) - Induced surface γ-dose rate (Svh^{-1}) after 2.5y of neutron irradiation at 5MWm^{-2} for 1ppm of each element placed in a steel matrix under first wall conditions (extended version of UKCTRIIIA library)

Element (Z)	50 years cooling time		100 years cooling time		main isotope(s) responsible
	Solid breeder blanket	Liquid breeder blanket	Solid breeder blanket	Liquid breeder blanket	
63-Eu	7.2 E-2	7.2 E-2	5.3 E-3	5.1 E-3	^{152}Eu, ^{150}Eu, ^{154}Eu
64-Gd	5.5 E-5	5.1 E-5	1.3 E-6	1.2 E-6	^{154}Eu, ^{152}Eu, ^{150}Eu
65-Tb	6.3 E-3	5.3 E-3	5.0 E-3	4.2 E-3	^{158}Tb
66-Dy	4.5 E-6	3.3 E-6	3.5 E-6	2.6 E-6	^{158}Tb
67-Ho	8.5 E-4	8.1 E-4	8.2 E-4	7.9 E-4	^{166m}Ho
68-Er	7.9 E-7	6.8 E-7	7.6 E-7	6.6 E-7	^{166m}Ho
69-Tm	4.0 E-7	3.6 E-7	3.9 E-7	3.6 E-7	^{166m}Ho
70-Yb	4.0 E-8	4.0 E-8	4.8 E-9	3.4 E-9	^{178m}Hf
71-Lu	1.0 E-7	1.0 E-7	1.9 E-8	1.5 E-8	^{178m}Hf
72-Hf	1.6 E-5	1.3 E-5	5.2 E-6	4.1 E-6	^{178m}Hf
73-Ta	7.8 E-9	4.8 E-9	2.6 E-9	1.6 E-9	^{178m}Hf, ^{182}Ta
74-W	5.3 E-10	9.1 E-10	3.5 E-10	4.5 E-10	^{186m}Re (^{186}Re), ^{178m}Hf
75-Re	2.2 E-9	2.8 E-9	2.2 E-9	2.7 E-9	^{186m}Re (^{186}Re)
76-Os	2.3 E-4	2.5 E-4	2.0 E-4	2.2 E-4	^{192m}Ir (^{192}Ir)
77-Ir	1.1 E-3	1.0 E-3	1.0 E-3	8.6 E-4	^{192m}Ir (^{192}Ir)
78-Pt	3.6 E-7	2.6 E-7	3.1 E-7	2.3 E-7	^{192m}Ir (^{192}Ir)
79-Au	-	-	-	-	-
80-Hg	-	-	-	-	-
81-Tl	-	-	-	-	-
82-Pb	9.1 E-8	3.6 E-8	3.2 E-8	1.3 E-8	^{207}Bi, ^{208}Bi
83-Bi	6.5 E-4	4.6 E-4	2.3 E-4	1.6 E-4	^{207}Bi, ^{208}Bi

Table III: Summary of element acceptability in first wall structural materials from considerations of long term γ-dose rate level

Permitted range mass percent	100y cooling time 'hands-on' limit	50y cooling time, 'recycling' limit
<0.1 ppm	Ag, Eu, Tb, Ho, Ir	-
0.1 - 1ppm	Nb, Os, Bi	Eu
1 - 10ppm	Co, Pd, Cd, Xe, Sm, Gd, Dy, Hf	Co, Ag, Tb, Ir
10 - 100ppm	Al, Kr, Cs, Ba, Nd, Er, Tm, Pt	Nb, Ho, Os, Bi
100 - 1000ppm	Sc, Ni, Cu, Mo, Pb	Ni, Cu, Cs, Ba, Sm, Gd, Hf
1000ppm - 1%	Ti, Zr, Yb, Lu, Ta	Kr, Rh, Pd, Cd, Xe, Nd, Dy
1% - 10%	Ca, Br, Rb, Ru, In, W, Re	Al, Sc, Mo, Er, Tm, Lu, Pt
10% - 90%	Si, Cl, K, Fe, Zn, Rh, Sn, La, Ce	Na, Ti, Fe, Zn, Rb, Sn, Yb, Pb
No limit	H, He, Li, Be, B, C, N, O, F, Ne, Na, Mg, P, S, Ar, V, Cr, Mn, Ga, Ge, As, Se, Sr, Y, Sb, Te, I, Pr, Au, Hg, Tl	H, He, Li, Be, B, C, N, O, F, Ne, Mg, Si, P, S, Cl, Ar, K, Ca, V, Cr, Mn, Ga, Ge, As, Se, Br, Sr, Y, Zr, Ru, In, Sb, Te, I, La, Ce, Pr, Ta, W, Re, Au, Hg, Tl

Table IV: Allowed mass ppm for all restricted elements according to the 'hands-on'
contact dose rate criterion after 100y cooling time, including
bremsstrahlung corrections and comparison with other authors' results
(NR = no restrictions).

Element	Present Study	Jarvis results [7]	Ponti results [15]	Element	Present Study	Jarvis results [7]	Ponti results [15]
13-Al	46	10-1000	100-500	49-In	5.1%	1-10%	NR
14-Si	71%	10-50%	20%	50-Sn	*0.6%	10-1000	10-50
15-P	NR	NR	NR	51-Sb	NR	NR	0.1%
16-S	NR	NR	NR	52-Te	NR	NR	5%
17-Cl	*0.86%	0.1-1%	5%	53-I	NR	NR	NR
18-Ar	*27	-	50	54-Xe	9.3	-	20%
19-K	*30	1-10	100	55-Cs	21	NR	100-500
20-Ca	*0.4%	10-1000	0.1-1%	56-Ba	17	1-10	10-50
21-Sc	0.07%	10-1000	2%	57-La	21%	0.1-1%	1-5%
22-Ti	0.26%	0.1-1%	5-10%	58-Ce	19%	NR	5%
23-V	NR	NR	NR	59-Pr	NR	NR	NR
24-Cr	NR	NR	NR	60-Nd	61	NR	0.1-0.5%
25-Mn	NR	NR	NR	62-Sm	6	NR	10
26-Fe	19%	NR	NR	63-Eu	0.005	<1	0.01
27-Co	2.5	0.1-1%	5	64-Gd	20	0.1-1%	1
28-Ni	0.04%	0.1-1%	0.1%	65-Tb	0.005	<1	0.01
29-Cu	0.08%	1-10%	0.1%	66-Dy	7	10-1000	10-50
30-Zn	16%	1-10%	50%	67-Ho	0.03	NR	0.05
31-Ga	NR	NR	NR	68-Er	33	10-1000	1-10
32-Ge	NR	NR	NR	69-Tm	64	10-1000	100
33-As	NR	NR	NR	70-Yb	0.5%	NR	0.5%
34-Se	NR	NR	NR	71-Lu	0.13%	NR	1
35-Br	2.8%	NR	5%	72-Hf	5	NR	1
36-Kr	96	-	.1%	73-Ta	0.93%	NR	50
37-Rb	1.4%	0.1-1%	1%	74-W	7.1%	NR	0.5%
38-Sr	NR	10-1000	5%	75-Re	*680	10-1000	500
39-Y	NR	NR	NR	76-Os	0.13	NR	1-5
40-Zr	0.64%	10-1000	1-5%	77-Ir	0.025	<1	0.1
41-Nb	0.2	1-10	1	78-Pt	81	0.1-1%	50
42-Mo	120	10-1000	50	79-Au	NR	NR	50%
44-Ru	1.6%	1-10%	1-5%	80-Hg	NR	NR	NR
45-Rh	89%	NR	NR	81-Tl	NR	NR	NR
46-Pd	5	NR	10-50	82-Pb	0.08%	NR	1-5%
47-Ag	0.008	<1	0.01	83-Bi	0.11	<1	1
48-Cd	3.7	10-1000	20				

* significant bremsstrahlung correction

Table V

Composition of LA7 and OPTSTAB Steels (wt%)

Steel type	C	Si	Mn	Cr	W	V	N	Ta	Fe
LA7	0.15	0.4	0.75	11.0	3.0	0.25	0.06	-	84.4
OPTSTAB	0.08	0.875	11.5	14.5	2.0	-	0.3	1.25	69.5

Table VI

Present estimates of the impurity levels in commercial
production of low-activation steels

Element	Al	K	Ca	Co	Ni	Cu	Zr	Nb	Mo	Ag
Level (ppm)	10	2	2	10	100	50	30	0.2	50	0.5
Element	Sn	Ba	Ce	Nd	Sm	Eu	Tb	Ir	Bi	-
Level (ppm)	50	2	4	2	0.5	0.2	0.5	0.1	5	-

Table VII - Specifications for isotopic tailoring for some elements (2.5 years operation at 5 MWm^{-2}).

Isotope	Natural Abundance (wt%)	Typical percentage in alloys (wt%)	50y - recycling	100y - hands-on
			Allowed abundance (wt%)	Allowed abundance (wt%)
^{54}Fe	5.80		*100	100
^{56}Fe	91.72	100%	*79.4	100
^{57}Fe	2.20		*0.5	34.0
^{58}Fe	0.28		*79 ppm	0.065
^{58}Ni	67.40		0.5	0.92
^{60}Ni	26.66		0.013	0.024
^{61}Ni	1.17	10%	0.12	0.22
^{62}Ni	3.79		1.24	1.82
^{64}Ni	0.99		100	1.64
^{92}Mo	14.22		100	0.77
^{94}Mo	9.05		4.8	3.4-3
^{95}Mo	15.75		100	0.09
^{96}Mo	16.67	5%	100	2.51
^{97}Mo	9.65		100	9.37
^{98}Mo	24.62		100	0.46
^{100}Mo	10.03		100	0.48
^{46}Ti	7.68		100	53.4
^{47}Ti	7.16		100	100
^{48}Ti	73.91	5%	100	1.0
^{49}Ti	5.62		100	7.85
^{50}Ti	5.63		100	100
^{204}Pb	1.38		100	100
^{206}Pb	23.96	100%	100'	100
^{207}Pb	22.08		100	100
^{208}Pb	52.60		8.9	0.062

* 5 cycles considered in this case.

(a)

Zone	Dimensions (m)	Material	Volume fraction
Plasma	0.0–0.825	–	–
Erosion layer	1.853 – 1.863	Steel	1.0
First wall	1.863 – 1.865	Steel	1.0
	1.865 – 1.882	Steel	0.20
		$Li_{17}Pb_{83}$ (90% ^6Li)	0.51
		Water	0.29
	1.882 – 1.885	Steel	1.0
Blanket	1.885 – 2.484	Steel	0.11
		$Li_{17}Pb_{83}$ (90% ^6Li)	0.49
		Water	0.08
		Void	0.32
Reflector/shield	2.484 – 2.784	Steel	1.0

(b)

Zone	Dimensions (m)	Material	Volume fraction
Plasma	0.0 – 1.31	–	–
Tile protection	2.178 – 2.181	Tungsten	1.0
First Wall	2.181 – 2.184	Copper	1.0
Cooling tubes	2.184 – 2.194	Inconel	0.15
Multiplier/breeder	2.194 – 2.394	Beryllium	0.60
		Li_2SiO_3 (30% ^6Li)	0.15
		Ferritic steel	0.075
		Helium	0.175
Breeder	2.394 – 2.914	Li_2SiO_3 (30% ^6Li)	0.75
		Ferritic steel	0.075
		Helium	0.175
Reflector/shield	2.914 – 3.214	Steel	1.0

Fig. 1 Dimensions and material concentrations for:

a) water-cooled liquid breeder blanket

b) helium-cooled solid breeder blanket
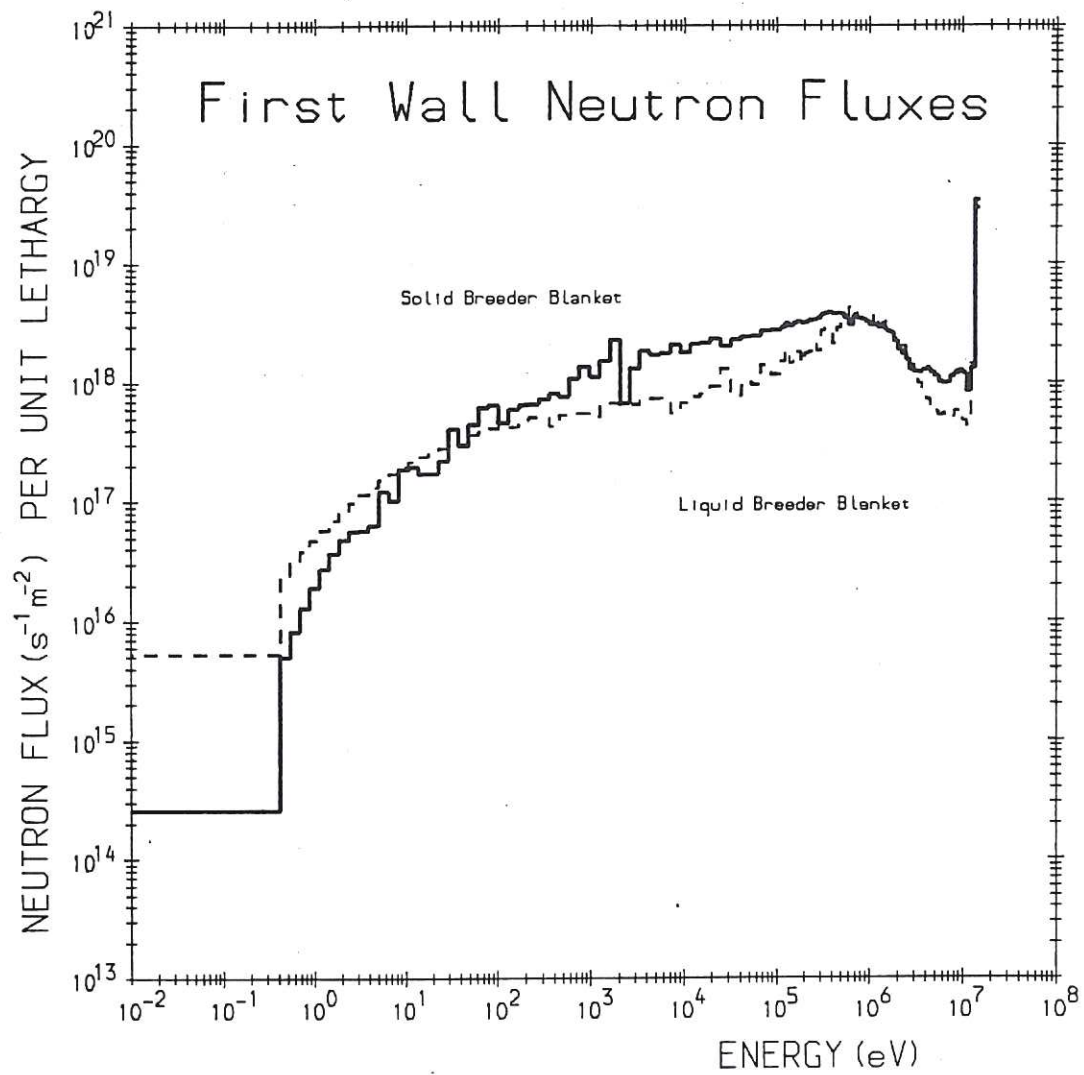
Fig. 2 Comparison between the first wall neutron flux corresponding to a solid breeder and to a liquid breeder blanket design.
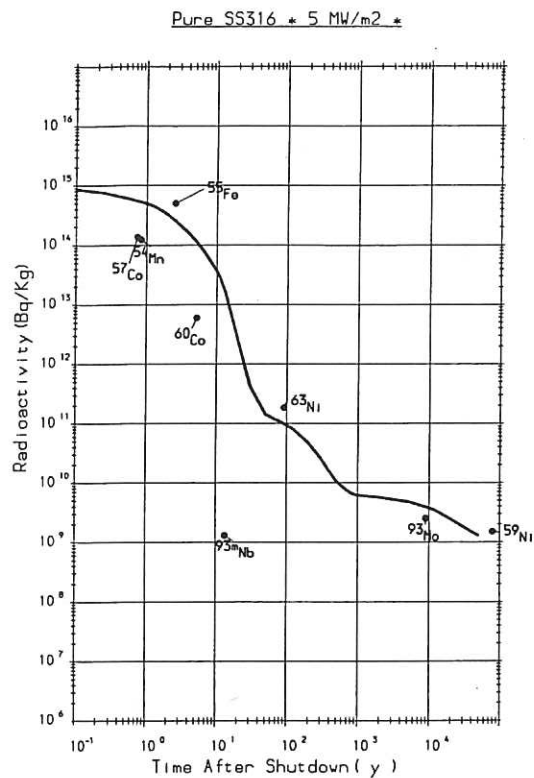
Fig. 3-A Radioactivity (Bqkg^{-1}) vs. cooling time for SS316 (pure) subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
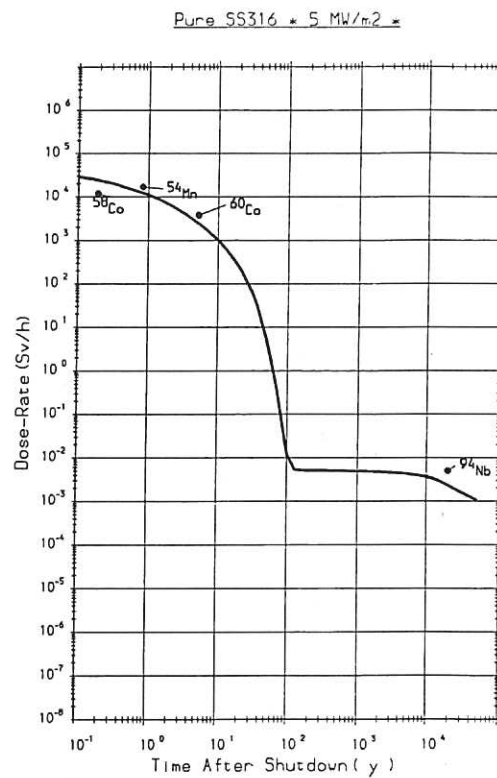
Fig. 3B Contact γ-dose rate (Svh^{-1}) vs. cooling time for SS316 (pure) subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
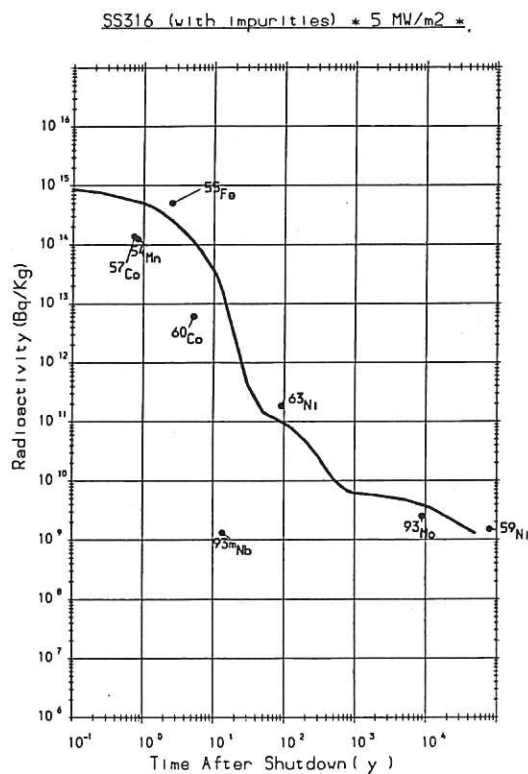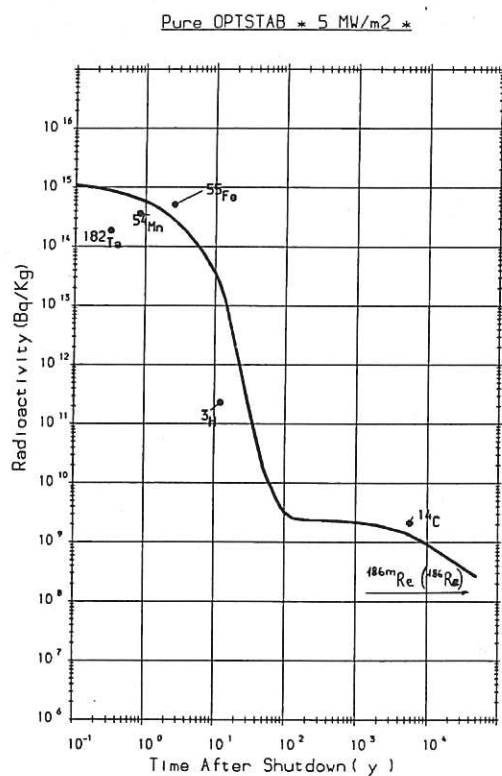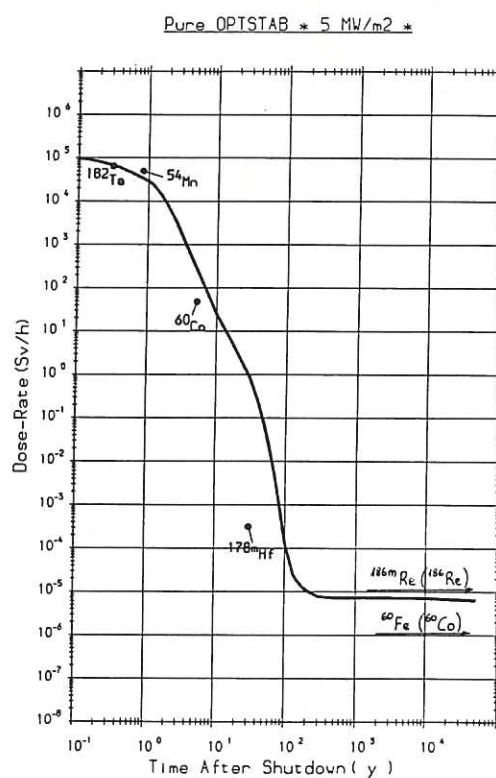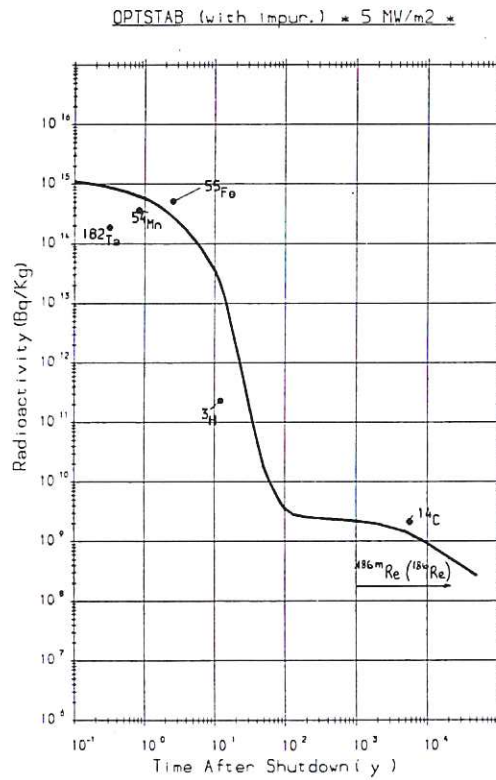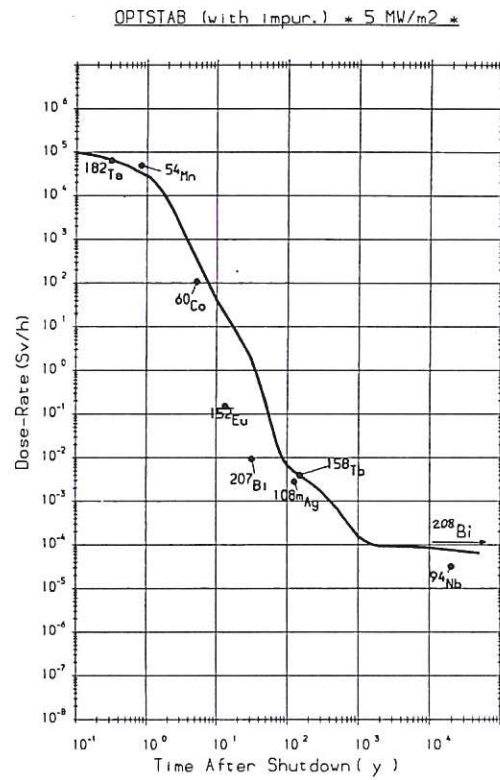
Fig. 4A Radioactivity (Bqkg^{-1}) vs. cooling time for SS316 (with impurities) subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
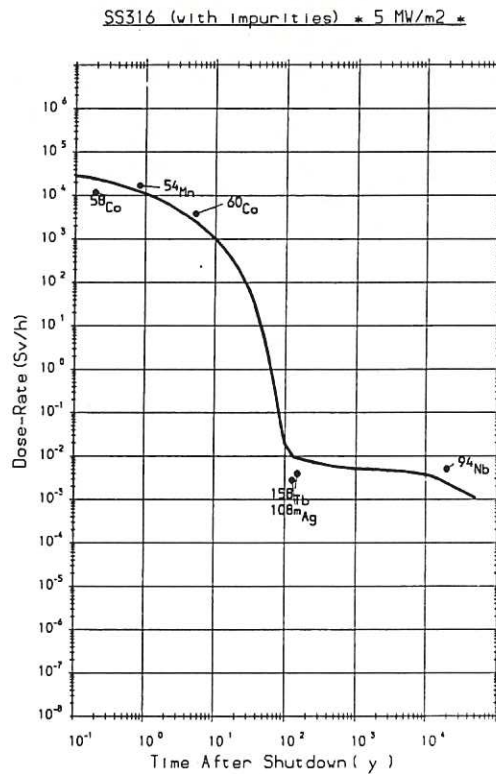
Fig. 4B Contact γ-dose (Svh^{-1}) vs. cooling time for SS316 (with impurities) subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
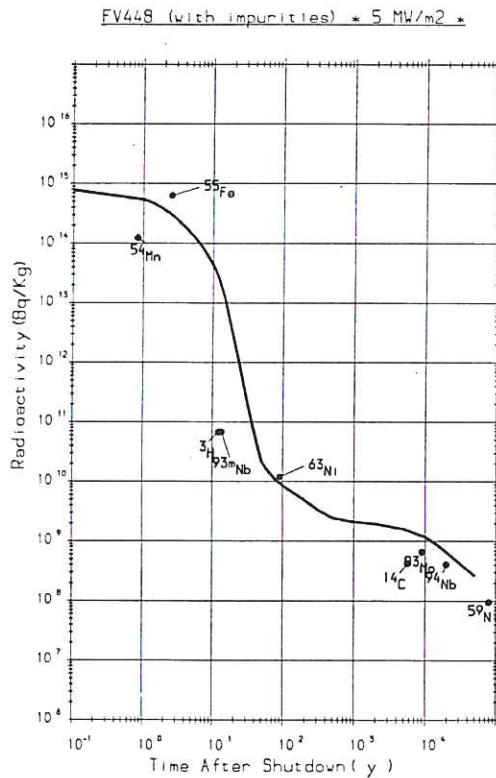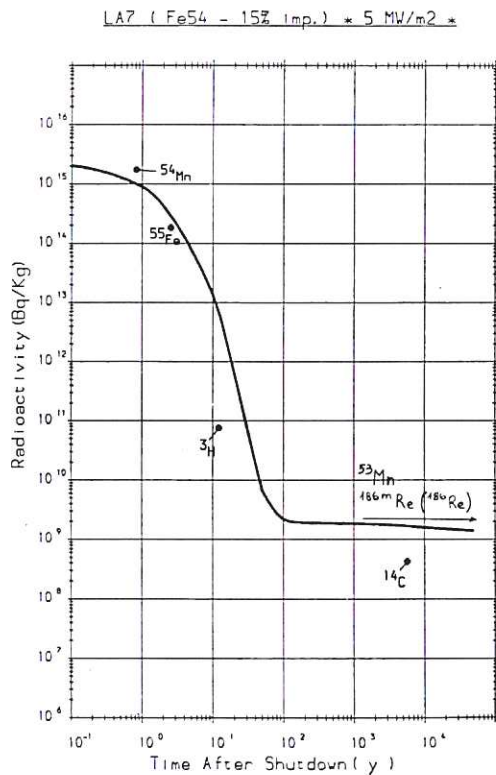
Fig. 5A Radioactivity (Bqkg^{-1}) vs. cooling time for FV448 steel subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
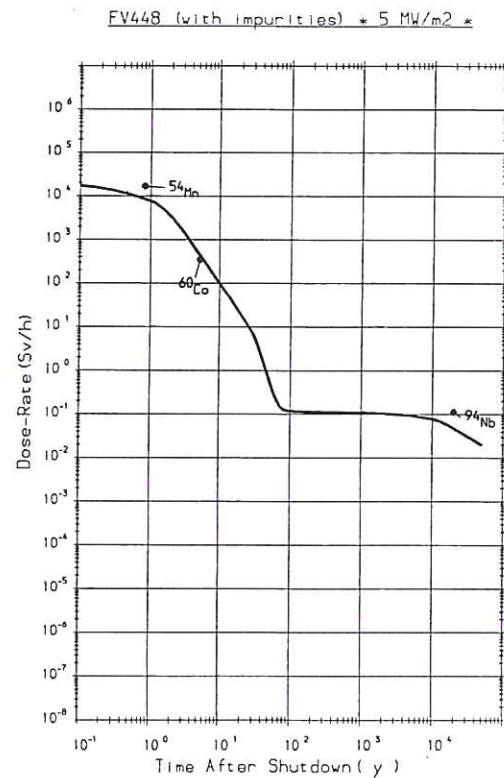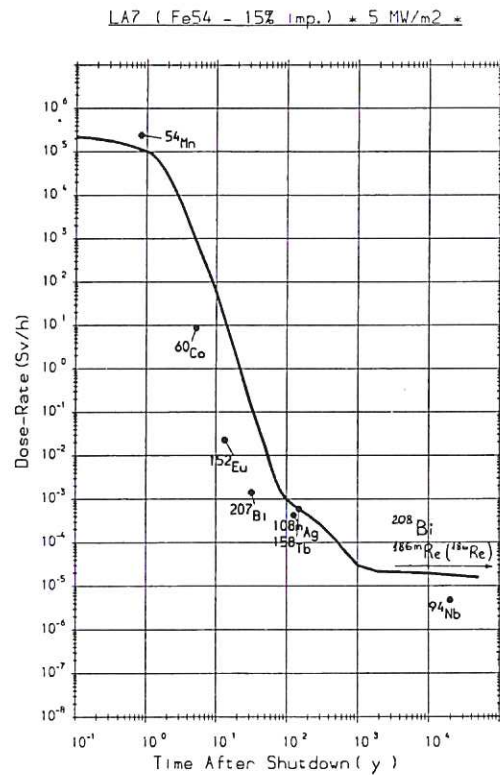
Fig. 5B Contact γ-dose rate (Svh^{-1}) vs. cooling time for FV448 steel subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
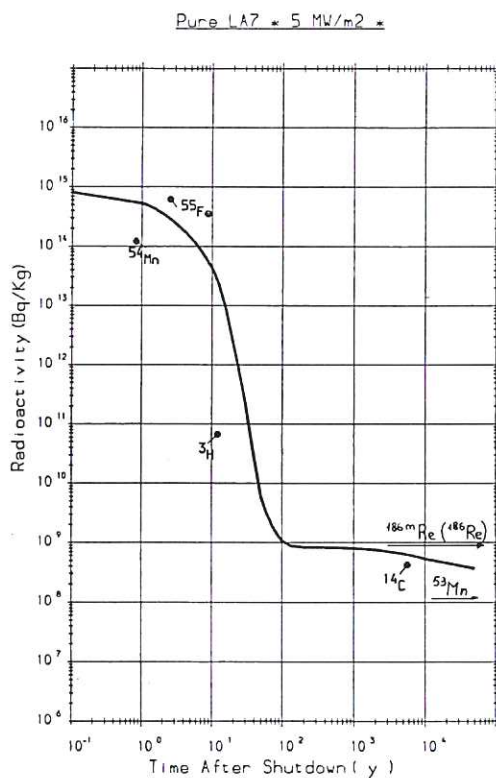
Fig. 6A Radioactivity (Bqkg^{-1}) vs. cooling time for pure LA7 steel subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
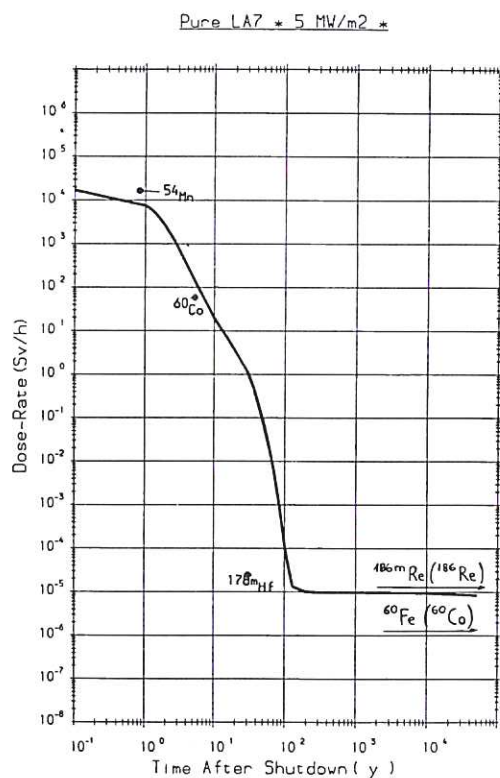
Fig. 6B Contact γ-dose rate (Svh^{-1}) vs. cooling time for pure LA7 steel subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
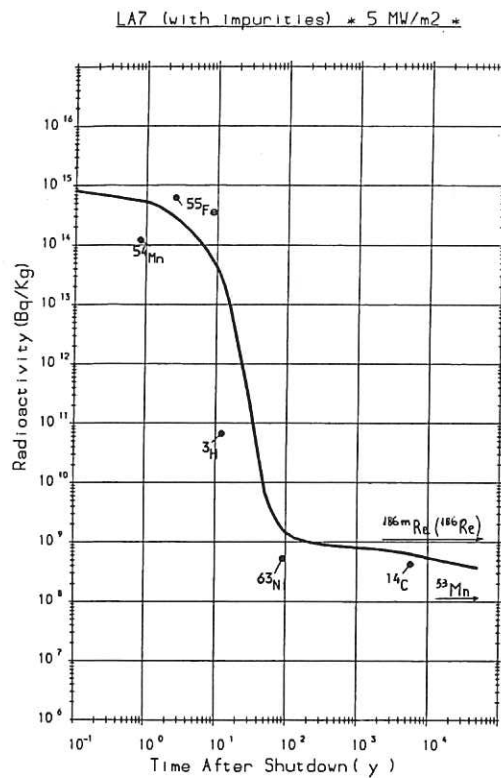
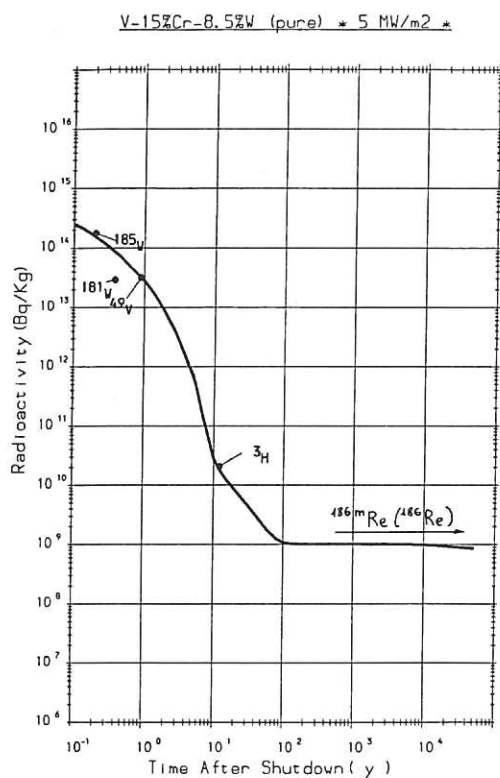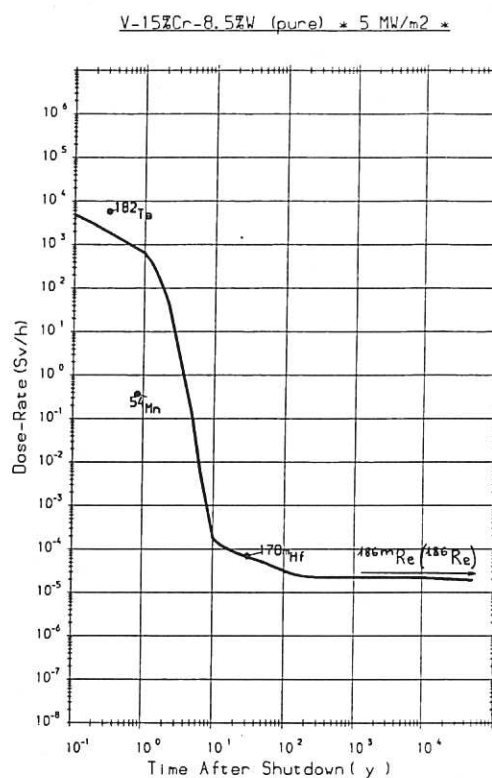Fig. 7A Radioactivity (Bqkg^{-1}) vs. cooling time for LA7 steel (with impurities) subjected to first wall operating conditions (2.5y exposure to $5\,MW\,m^{-2}$).
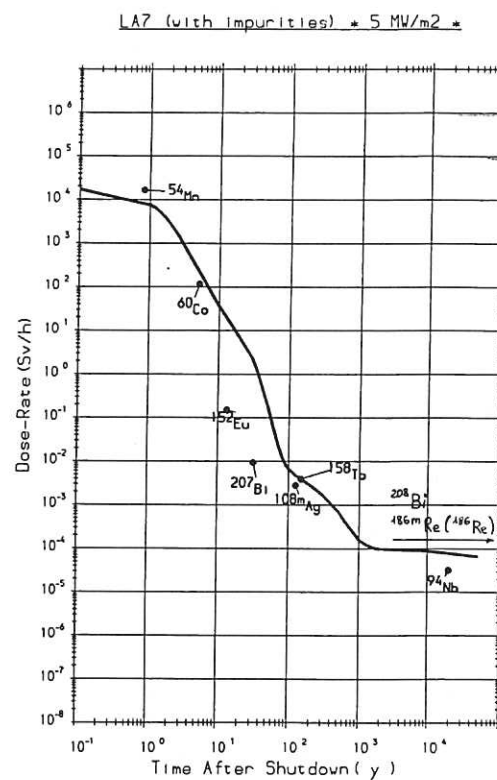
Fig. 7B Contact γ-dose rate (Svh^{-1}) vs. cooling time for LA7 steel (with impurities) subjected to first wall operating conditions (2.5y exposure to $5\,MW\,m^{-2}$).
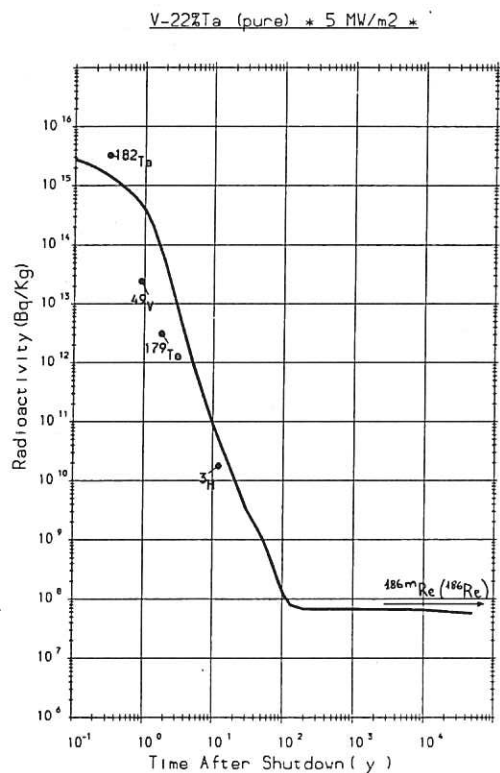
Fig. 8A Radioactivity(Bqkg^{-1}) vs. cooling time for pure OPTSTAB steel subjected to first wall operating conditions (2.5y exposure to $5\,MWM^{-2}$).
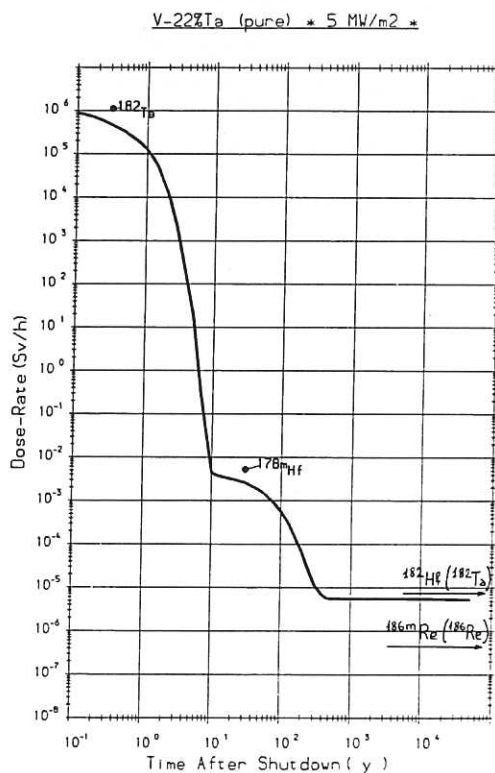
Fig. 8B Contact γ-dose rate (Svh^{-1}) vs. cooling time for pure OPTSTAB steel subjected to first wall operating conditions (2.5y exposure to $5\,MW\,m^{-2}$).

Fig. 9A Radioactivity (Bqkg^{-1}) vs. cooling time for OPTSTAB steel (with impurities) subjected to first wall operating conditions (2.5y exposure to 5 MWm^{-2}).

Fig. 9B Contact γ-dose rate (Svh^{-1}) vs. cooling time for OPTSTAB steel (with impurities) subjected to first wall operating conditions (2.5y exposure to 5 MWm^{-2}).

Fig. 10A Radioactivity (Bqkg^{-1}) vs. cooling time for tailored LA7 steel subjected to first wall operating conditions (2.5y exposure to 5 MWm^{-2}).

Fig. 10B Contact γ-dose rate (Svh^{-1}) vs. cooling time for tailored LA7 steel subjected to first wall operating conditions (2.5y exposure to 5 MWm^{-2}).
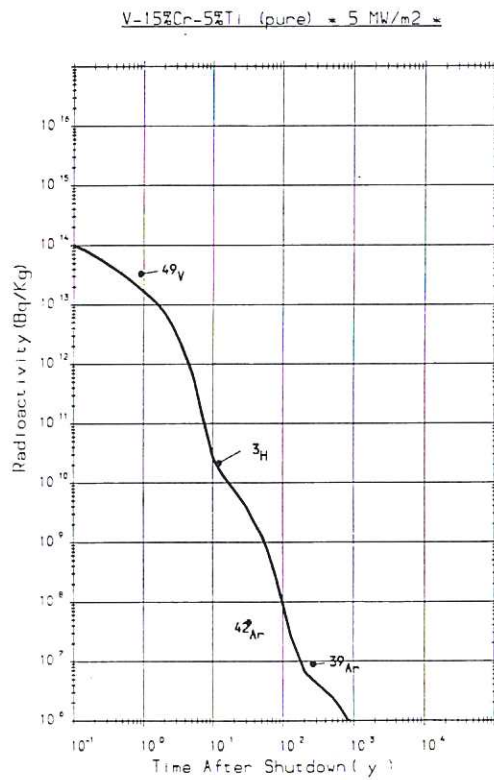
Fig. 11A Radioactivity (Bqkg^{-1}) vs. cooling time for pure V-Cr-W alloy subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
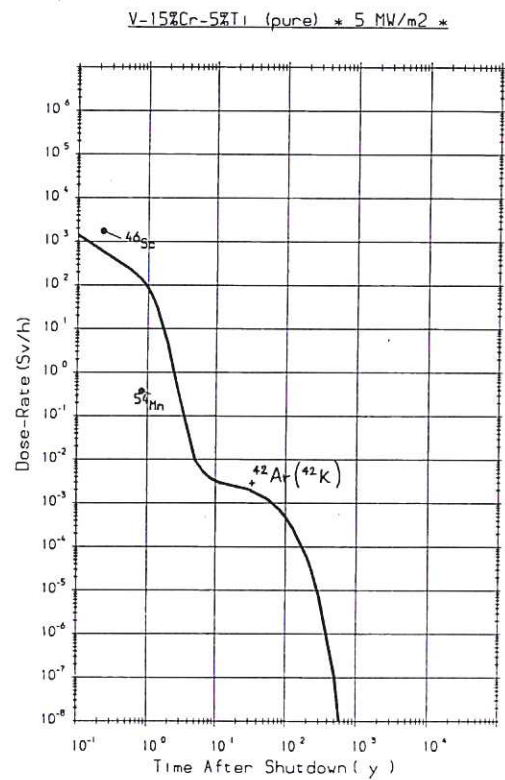
Fig. 11B Contact γ-dose rate (Svh^{-1}) vs. cooling time for pure V-Cr-W alloy subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
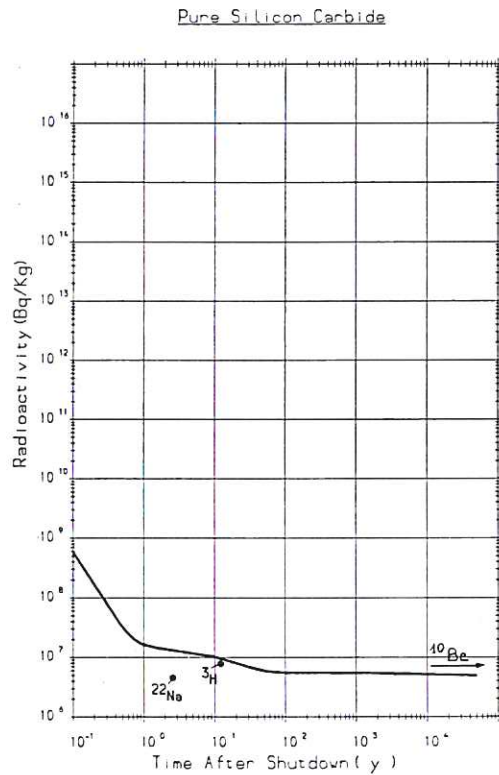
Fig. 12A Radioactivity (Bqkg^{-1}) vs. cooling time for pure V-Ta alloy subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).
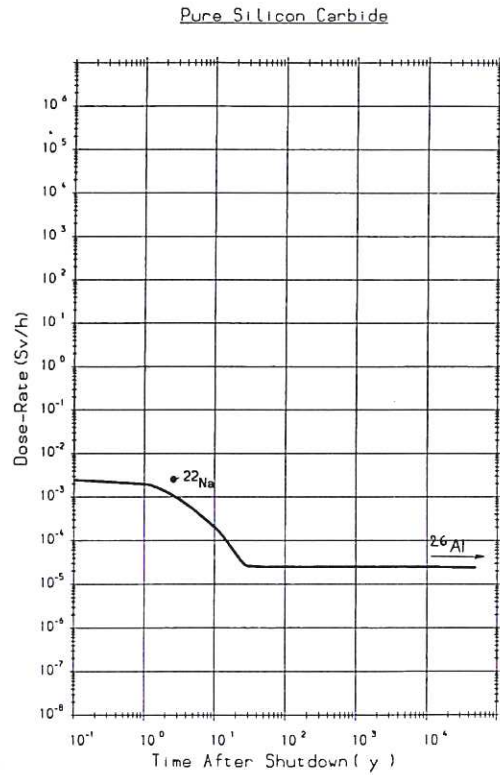
Fig. 12B Contact γ-dose rate (Svh^{-1}) vs. cooling time for pure V-Ta alloy subjected to first wall operating conditions (2.5y exposure to 5 MW m^{-2}).

Fig. 13A Radioactivity (Bqkg^{-1}) vs. cooling time for pure V-Cr-Ti alloy subjected to first wall operating conditions (2.5y exposure to 5MWm^{-2}).
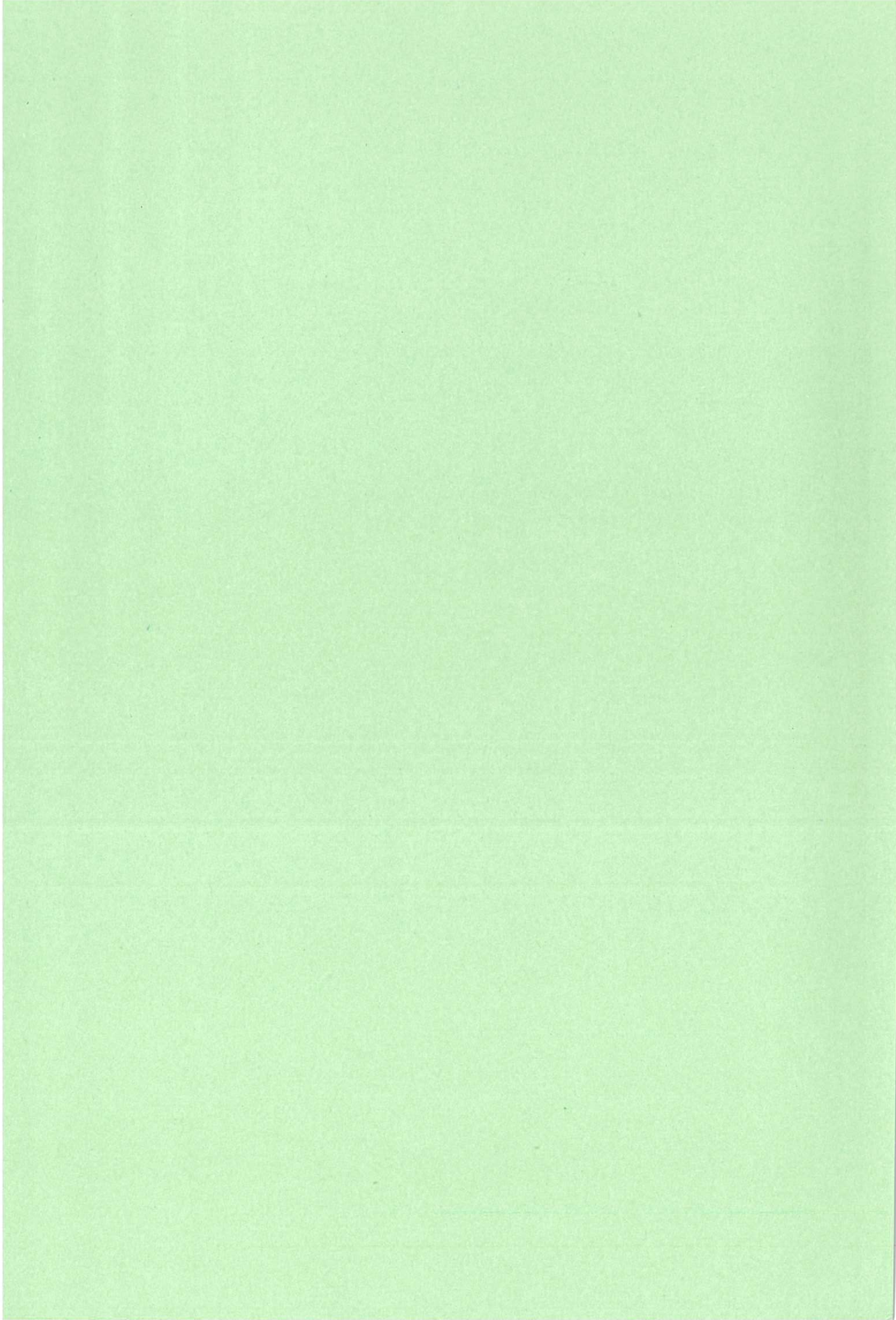
Fig. 13B Contact γ-dose rate (Svh^{-1}) vs. cooling time for pure V-Cr-Ti alloy subjected to first wall operating conditions (2.5y exposure to 5MWm^{-2}).

Fig. 14A Radioactivity (Bqkg^{-1}) vs. cooling time for pure silicon carbide subjected to first wall operating conditions (2.5y exposure to 5MWm^{-2}).

Fig. 14B Contact γ-dose rate (Svh^{-1}) vs. cooling time for pure silicon carbide subjected to first wall operating conditions (2.5y exposure to 5MWm^{-2}).