EUROPEAN COMMISSION
5th EURATOM FRAMEWORK PROGRAMME 1998-2004
KEY ACTION : NUCLEAR FISSION

HTR-N1

European Project for the development of HTR Technology – Waste and Fuel Cycle Studies

CONTRACT N°
FIKI-CT-2001-00169

WP4
HTR Specific Wastes – Assessment of the Advantages of Graphite Treatment

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Dissemination level : CO
Document Number: HTR-N-05/05-D-4.4.1
Deliverable Number: 4.4.1

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C6818/TR/001
Issue 01
January 2004

DOCUMENT ISSUE RECORD
(engineering documents)

NNC

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Document Title :	HTR-N WP4 HTR Specific Wastes - Activated Graphite
Project Reference:	C6818

Purpose of Issue : Verified for use

Security Class : Commercial-in-Confidence

Issue	Description of Amendment	Originator/ Author	Checker	Approver	Date
01 draft	Issue for internal verification	L Walker	A N Nuttall		1/4/2005
01	First Issue	L Walker	A N Nuttall	H M Beaumont	18/4/05

Total number of pages:	Intro:	(i)-(iv)	Text	1-6	Tables	T1-T6	Figures	F1-F6	Appendices	-

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3050aMay2003 Controlling procedure - QP7, QP11, QP40 DSC Ref

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1 Introduction

The purpose of this work is to assess the advantages of graphite treatment and in particular the thermal treatment investigated experimentally as part of Task 4.3 of HTR-N1. HTR-N1 is one of a family of HTR projects being studied under the EC's 5th Framework programme. HTR-N1 itself, being compiled in response to EC contract FIKI-CT-2000-00169, has five primary work packages, dealing respectively with nuclear physics validation (separate packages for block type of reactors and pebble bed type reactors), fuel cycle, HTR specific wastes and the long term behaviour of disposed spent fuel. This report forms part of work package 4 (WP4).

Experimental work, undertaken within WP4 of HTR-N1, has established release fractions of key volatile radionuclides following the thermal treatment of irradiated graphite samples. This report presents an assessment of the anticipated effect on reactor graphite activity of applying this thermal treatment post irradiation. Consideration is given to the benefit of such a treatment and how the graphite residue could subsequently be disposed of more easily. The main part of this report considers disposal of the treated graphite in the context of UK regulations. Since the waste category definition and disposal criteria are country specific it is anticipated that addenda might be prepared by other participating countries to assess the advantage of graphite treatment from their perspective. These can then be appended to the main report to provide a synthesised report presenting the combined findings of HTR-N1, Task 4.4: "Assessment of the Advantages of Graphite Treatment".

2 Graphite Arisings

The activities and masses of the graphite are those predicted to arise from the GT-MHR pessimistic block design of HTR (Ref 1) generating 280MWe.

The graphite to be considered can be broken down into three distinct parts:

1. Replaceable reflector graphite. There will be 3600te of this graphite generated during the 60yr lifetime of the reactor. Every six yrs 360te of this graphite is changed.
2. Integral with the fuel. There will be 2340te of this graphite generated during the 60yr lifetime of the reactor. The whole core is changed every 2.3yrs (89te). Post irradiation the graphite may be separated from the fuel kernels.
3. Permanent core graphite. There will be 240te of this graphite that stays in the core for the 60yr lifetime of the reactor.

Section 3 of this report assesses each of the three types of graphite separately in terms of the activity of the waste and the likely effects of treatment. It is considered that the inventory of the waste would be similar for a pebble bed reactor design of approximately the same power.

3 Activity Assessment

Activation of the graphite, including impurities within the graphite, gives rise to a series of radioactive isotopes that require long-term storage or treatment.

Activities at the three core dwell times (one for each of the graphite types in Section 2) have been determined (if necessary by interpolation) from the various times of irradiation available in the analysis reported in Ref 1.

In order to identify the benefit of increasing periods of safestore before disposal the activities at various decay times post removal from the reactor have been calculated and are tabulated.

The activities are presented on the basis that the graphite has undergone a thermal treatment to remove volatiles. The scenarios are as follows:

1. The experimentally verified thermal treatment can remove 23.5% of the ^{14}C and 69.4% of the ^{3}H. This is consistent with case with 960°C pressurised steam treatment (7.4kPa – flow rate 660ml/min) in Ref 2.
2. The temperature in Scenario 1 (above) was limited by experimental limitations. Further experiments are to be undertaken at higher temperatures with the expectation that the fractional values for removal of volatile ^{14}C and ^{3}H will increase. To provide an indication of the upper bound that might be achievable, a theoretical case is postulated that removes all the volatile ^{14}C and ^{3}H from the graphite. This is equal to all the ^{14}C produced from N activation and all the tritium.

The graphite also absorbs nitrogen from air that has not been removed from the He coolant and this also contributes to the ^{14}C in the graphite. This additional source of ^{14}C has not been included in the activity calculations detailed in Ref 1, but it will reside at the surface of the graphite and is assumed to be totally removed from graphite that undergoes thermal treatment.

All activities are compared against the UK LLW limit of 12GBq/te β/γ (i.e. 1.2E4Bq/g).

3.1 Replaceable Reflector Graphite

The replacement period for this graphite is 6yrs.

Tables 1a and 1b present the specific activity of the graphite for times up to 80yrs post removal from the reactor.

Figure 1 and Figure 2 present the fractional contribution to the total activity from the main isotopes for the experimental and the theoretical volatile removal treatments.

3.2 Graphite Integral with the Fuel

The replacement period for this graphite is 2.3 yrs.

Tables 2a and 2b present the specific activity of the graphite for times up to 80yrs post removal from the reactor. (The data presented is slightly conservative in that it relates to a 3yr reactor dwell.)

Figure 3 and Figure 4 present the fractional contribution to the total activity from the main isotopes for the experimental and the theoretical volatile removal treatments.

3.3 Permanent Core Graphite

The replacement period for this graphite is 60 yrs.

Tables 3a and 3b present the specific activity of the graphite for times up to 80yrs post removal from the reactor.

Figure 5 and Figure 6 present the fractional contribution to the total activity from the main isotopes for the experimental and the theoretical volatile removal treatments.

4 Discussion of Activity Results

The results for the analysis show that the activity of the graphite separated from the fuel may fall below the UK LLW upper limit after thermal treatment and a period of safestore. For all other reactor graphite the specific activity, after thermal treatment and an extended period of safestore before final disposal, remains within the UK ILW category. The following sections outline in detail the results for each of the graphite waste streams.

4.1 Replaceable reflector graphite

For the experimentally based removal scheme (i.e. Scenario 1 in Section 3) ^{3}H and ^{14}C (also ^{55}Fe for times up to 10yrs decay) are the main contributors to the activity at all times for the considered decay times, of up to 80yrs post reactor removal (Fig 1) and the waste is always above the LLW limit (Table 1a).

With the theoretical maximum removal of volatiles from the graphite the waste is still over four times the LLW limit for the considered decay times (Table 1b). The main contributor to the activity (for the theoretical removal of volatile scheme) comes from ^{14}C, except for times up to 20yrs decay where ^{55}Fe dominates (Fig 2).

However, for both volatile removal schemes the presence of ^{63}Ni in the graphite is enough, by itself, to produce activity in the waste above LLW levels for the considered decay times by a factor of approximately 2.

4.2 Graphite initially Integral with the Fuel

The graphite is assumed successfully separated from the fuel and free from fuel contamination.

For the experimentally based volatile removal scheme ^{3}H and ^{14}C (also ^{60}Co for times up to 10yrs decay) are the main contributors to the activity at all times for the considered decay times, of up to 80yrs post reactor removal (Fig 3). Extending the period of safestore to 100yrs (extrapolation from Table 2a) would enable the waste to be re-categorised as LLW. With the theoretical maximum removal of volatiles from the graphite the waste falls below the LLW limit after 40yrs (Table 2b). The main contributors to the activity (for the theoretical removal of volatile scheme) come from ^{60}Co at times less than 30yrs and ^{63}Ni for all later times (Fig 4). The activity for the ^{14}C is below the LLW limit at all times considered.

The presence of ^{63}Ni in the graphite contributes significantly to the overall activity of the waste for both treatment schemes after 40yrs, but the activity of the ^{63}Ni is below the LLW limit at all times.

4.3 Permanent core graphite

For the experimentally based removal scheme ^{3}H and ^{14}C (also ^{55}Fe at 0yrs decay) are the main contributors to the activity at all times for the considered decay times, of up to 80yrs post reactor removal (Fig 5) and the waste is always above the LLW limit (Table 3a).

With the theoretical maximum removal of volatiles from the graphite the waste is still over twenty times the LLW limit for all decay times up to 80yrs post reactor removal (Table 3b). The main contributor to the activity (for the theoretical removal of volatile scheme) comes from ^{14}C, except for 0yrs decay where ^{55}Fe dominates (Fig 6).

However, for both volatile removal schemes the presence of ^{63}Ni in the graphite is enough, by itself, to produce activity in the waste above LLW levels for all times post removal from the reactor by a factor of at least four.

4.4 AVR Graphite Measured Specific Activities

Experimental data from an operating HTR is available, from the low power AVR.

Table 4a outlines the measured specific activities for the two types of graphite from the AVR (from Ref 2).

Activity data for key isotopes after removal of volatiles are presented for both experimental treatment (Table 4b) and theoretical limit (Table 4c) - as per the HTR analysis. Tables 4b and 4c show that the specific activities for the ^{3}H (except for the theoretical case – Table 4c), ^{14}C and ^{63}Ni would place the waste above the LLW limit and would remain above the limit for the 80yrs post removal period considered in this report.

5 Disposal of Waste in the UK

The Environment Agency has responsibility in relation to the environmental impact of the storage and ultimate final management of radioactive waste produced on licensed nuclear sites. In the UK, LLW solid waste is disposed of to Drigg. To be accepted at Drigg the waste is required to be LLW (i.e. <1.2E4Bq/g β/γ) and also must meet separate ^{14}C limits. Under the present Drigg operating limits they cannot accept more than 50GBq of ^{14}C in any one year. The total activity of ^{14}C expected from a single reactor (after 60yrs of operation and 80yrs of decay) is 3.0E14Bq (based on the thermal treatment, experimental results), which would require 6000 yrs of Drigg operation even if the waste could be diluted to LLW levels and sent to Drigg. *Note that the deliberate dilution of waste is not allowed in the UK and this option is thus considered impractical.*

In the UK, storage of solid ILW waste requires the building of 'safestores' where typically grouted boxes of waste are expected to be stored until long-term Nirex ILW storage facilities have been constructed.

Recycling of the graphite is another option for disposal of the waste. However, the possibility of directly reusing graphite in another reactor is considered unlikely. Re-fabrication of purified graphite into nuclear graphite is an area that would require further investigation, as would the use of graphite as a filler for waste management purposes. In the UK graphite manufacturers are not optimistic that recycled graphite can be used outside the nuclear industry, particularly if significant ^{14}C remains in the material.

6 Other Issues

A series of additional treatments may be applied to the graphite that have potential to improve the waste disposal properties. These are outlined below.

6.1 Steam Oxidation of Radioactive Graphite followed by Re-Conversion to Carbon

The treatment already outlined for the graphite to remove the volatiles (^{14}C and the ^{3}H) would not solve the problem with the activity due to the ^{63}Ni. However, were the graphite to be steam oxidised and then reduced to re-collect the carbon then ^{63}Ni, along with all other non-volatile isotopes, would be expected to be left in the small amount of remaining residue. Experiments undertaken within WP4 of HTR-N1 have demonstrated that the residue left by the process consists of ~4% of the initial mass of the irradiated graphite.

For the graphite initially integral with the fuel, the treatment could be used to reduce the activity of the resultant carbonaceous product to less than LLW activity limits, without the need for an extended period of safestore. However, the ^{14}C present in the graphite would make it impossible to consign to the LLW repository at Drigg given their low acceptance limits for ^{14}C. If regarded as waste this purified carbon would thus have to be disposed of as ILW, alternatively it could be reformed into graphite and reused within the nuclear industry. Also, the small volume of residue (containing all the other isotopes) would be many times above the LLW activity limit.

6.2 Encapsulation

In the UK the accepted route for long-term storage of graphite has involved the use of encapsulation of the waste in a grouted steel box. Encapsulation of the graphite (either treated or untreated) will reduce the possibility of oxidation (the main route for release of gaseous ^{14}C) even for faults involving fire (providing package integrity is maintained). Such storage also reduces the possibility of contaminating the graphite with catalytic substances which would increase thermal oxidation rates. Use of encapsulation also reduces the probability of large particulate release during storage and for faults.

6.3 Densification

Compression of the graphite can be undertaken to achieve the maximum theoretical density of the material, thereby eliminating pores and voids and machine bores. Densification can be achieved by electrolytic and chemical means. The expected volume reduction of the waste is expected to be in the region of 20 to 40%. This is a new technology and has the potential to reduce the leeching of radionuclides through the graphite. The effectiveness of densification to reduce leeching is uncertain and would require further investigation.

Such leeching is expected (from experimental data) to be very low and indeed there have been suggestions to coat other radioactive wastes with carbon to reduce leeching rates during storage.

7 Conclusions

Of the HTR types of reactor graphite, only the radioactive graphite that was initially integral with the fuel is predicted to be capable of reduction to less than the UK LLW activity limits by the application of the thermal treatment verified by experiments undertaken as part of the HTR-N1, WP4 project. This would be after an approximate 100yrs of safestore.

Increasing the temperature of the thermal treatment might reduce this required period of safestore towards a more practical 40 years. To achieve the reduction to LLW, techniques would need to be developed to separate the graphite from the fuel without contamination. The graphite integral with fuel represents 37% of the radioactive graphite generated during the 60 years of operation and subsequent decommissioning of an HTR (the GT-MHR prismatic block design).

However, the remaining ^{14}C present in the treated carbon would still make it impossible to dispose of as LLW at Drigg (the UK LLW disposal site) given their low annual acceptance limits for ^{14}C.

For the other two types of HTR graphite, replaceable and permanent reflector, the activity arising solely from the ^{14}C forming part of the lattice is sufficient to assign the waste as ILW. Only isotope mass separation techniques would be effective in reducing the specific activity further.

Thus, there is little advantage in thermally treating the activated graphite if it continues to be perceived as a waste stream for HTR (requiring disposed as ILW within the UK).

There is an opportunity that the main mass of thermally treated graphite could be recycled within the nuclear industry. The refabrication of the purified carbonaceous product into reformed graphite and the subsequent reuse in HTR reactors still needs to be researched. Only a small active residue, up to 4% of the original reactor graphite mass, would then be regarded as waste for eventual disposal in an ILW repository.

8 References

1. HTR-N WP4, HTR Specific Wastes, - Final Report, J M Turner et al, 63941, Issue 3, October 2003
2. Thermal Treatment of Radioactive Graphite as Decontamination Option, Tatjana Podruzhina, Interner Bericht FZJ-ISR-IB-554/04

Table 1a Replaceable Reflector Graphite: 6yrs Dwell Time - Activity after Removal from the Reactor: Experimental Volatile Removal

Isotope	0yrs decay Bq/g	10 yrs decay Bq/g	20 yrs decay Bq/g	30 yrs decay Bq/g	40 yrs decay Bq/g	50 yrs decay Bq/g	60 yrs decay Bq/g	70 yrs decay Bq/g	80 yrs decay Bq/g
10Be	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01
14C	4.87E+04	4.86E+04	4.85E+04	4.85E+04	4.84E+04	4.84E+04	4.83E+04	4.82E+04	4.82E+04
36Cl	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03
41Ca	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02
59Ni	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02
93Zr	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06
93Mo	8.07E+00	8.06E+00	8.04E+00	8.02E+00	8.01E+00	7.99E+00	7.98E+00	7.96E+00	7.95E+00
99Tc	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00
126Sn	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13
129I	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10
3H	3.56E+05	2.02E+05	1.15E+05	6.56E+04	3.73E+04	2.12E+04	1.21E+04	6.88E+03	3.92E+03
63Ni	5.12E+04	4.78E+04	4.46E+04	4.16E+04	3.88E+04	3.62E+04	3.38E+04	3.15E+04	2.94E+04
55Fe	5.66E+05	4.34E+04	3.33E+03	2.56E+02	1.96E+01	1.51E+00	1.16E-01	8.88E-03	6.81E-04
Total	**1.02E+06**	**3.44E+05**	**2.14E+05**	**1.58E+05**	**1.27E+05**	**1.08E+05**	**9.64E+04**	**8.89E+04**	**8.37E+04**
Factor Greater than LLW Limit	85	29	18	13	11	9	8	7	7

Table 1b Replaceable Reflector Graphite: 6yrs Dwell Time - Activity after Removal from the Reactor: Theoretical Volatile Removal

Isotope	0yrs decay Bq/g	10 yrs decay Bq/g	20 yrs decay Bq/g	30 yrs decay Bq/g	40 yrs decay Bq/g	50 yrs decay Bq/g	60 yrs decay Bq/g	70 yrs decay Bq/g	80 yrs decay Bq/g
10Be	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01	2.19E+01
14C	1.93E+04	1.93E+04	1.93E+04	1.93E+04	1.92E+04	1.92E+04	1.92E+04	1.92E+04	1.91E+04
36Cl	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03	1.55E+03
41Ca	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02	3.82E+02
59Ni	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02	2.77E+02
93Zr	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06	2.50E-06
93Mo	8.07E+00	8.06E+00	8.04E+00	8.02E+00	8.01E+00	7.99E+00	7.98E+00	7.96E+00	7.95E+00
99Tc	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00	1.24E+00
126Sn	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13	8.66E-13
129I	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10	5.40E-10
63Ni	5.12E+04	4.78E+04	4.46E+04	4.16E+04	3.88E+04	3.62E+04	3.38E+04	3.15E+04	2.94E+04
55Fe	5.66E+05	4.34E+04	3.33E+03	2.56E+02	1.96E+01	1.51E+00	1.16E-01	8.88E-03	6.81E-04
Total	**6.39E+05**	**1.13E+05**	**6.94E+04**	**6.33E+04**	**6.03E+04**	**5.77E+04**	**5.52E+04**	**5.29E+04**	**5.08E+04**
Factor Greater than LLW Limit	53.2	9.4	5.8	5.3	5.0	4.8	4.6	4.4	4.2

Table 2a Graphite Integral with the Fuel: 3yrs Dwell Time - Activity after Removal from the Reactor: Experimental Volatile Removal

Isotope	0yrs decay Bq/g	10 yrs decay Bq/g	20 yrs decay Bq/g	30 yrs decay Bq/g	40 yrs decay Bq/g	50 yrs decay Bq/g	60 yrs decay Bq/g	70 yrs decay Bq/g	80 yrs decay Bq/g
10Be	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01
14C	7.34E+03	7.33E+03	7.32E+03	7.31E+03	7.30E+03	7.29E+03	7.28E+03	7.27E+03	7.27E+03
36Cl	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02
41Ca	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01
59Ni	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01
79Se	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17
93Zr	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06
93Mo	5.66E+00	5.65E+00	5.64E+00	5.63E+00	5.62E+00	5.60E+00	5.59E+00	5.58E+00	5.57E+00
94Nb	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.64E-04	2.64E-04	2.64E-04
99Tc	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01
107Pd	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08
126Sn	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13
129I	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12
135Cs	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06
3H	2.27E+05	1.29E+05	7.36E+04	4.19E+04	2.38E+04	1.36E+04	7.72E+03	4.39E+03	2.50E+03
22Na	1.01E-01	7.02E-03	4.88E-04	3.40E-05	2.36E-06	1.64E-07	1.14E-08	7.94E-10	5.52E-11
54Mn	7.66E+03	2.30E+00	6.93E-04	2.09E-07	6.27E-11	1.89E-14	5.68E-18	1.71E-21	5.14E-25
55Fe	9.89E+04	7.59E+03	5.83E+02	4.47E+01	3.43E+00	2.63E-01	2.02E-02	1.55E-03	1.19E-04
60Co	2.24E+05	5.98E+04	1.60E+04	4.27E+03	1.14E+03	3.04E+02	8.13E+01	2.17E+01	5.80E+00
63Ni	6.22E+03	5.80E+03	5.41E+03	5.05E+03	4.71E+03	4.40E+03	4.10E+03	3.83E+03	3.57E+03
65Zn	8.68E+04	2.73E+00	8.56E-05	2.69E-09	8.43E-14	2.65E-18	8.31E-23	2.61E-27	8.20E-32
90Sr	8.78E-04	6.90E-04	5.43E-04	4.27E-04	3.35E-04	2.64E-04	2.07E-04	1.63E-04	1.28E-04
106Ru	2.28E-10	2.54E-13	2.82E-16	3.14E-19	3.49E-22	3.89E-25	4.33E-28	4.81E-31	5.35E-34
108mAg	1.20E-01	1.18E-01	1.16E-01	1.14E-01	1.12E-01	1.10E-01	1.09E-01	1.07E-01	1.05E-01
110mAg	4.99E+02	1.93E-02	7.46E-07	2.88E-11	1.12E-15	4.31E-20	1.67E-24	6.45E-29	2.49E-33
119mSn	1.15E-01	2.04E-05	3.64E-09	6.47E-13	1.15E-16	2.04E-20	3.63E-24	6.46E-28	1.15E-31
121mSn	3.11E-02	2.71E-02	2.36E-02	2.05E-02	1.79E-02	1.56E-02	1.35E-02	1.18E-02	1.03E-02
125Sb	3.86E+03	2.96E+02	2.27E+01	1.75E+00	1.34E-01	1.03E-02	7.89E-04	6.05E-05	4.65E-06
134Cs	2.73E+01	9.44E-01	3.26E-02	1.13E-03	3.90E-05	1.35E-06	4.66E-08	1.61E-09	5.57E-11
137Cs	9.70E-03	7.71E-03	6.13E-03	4.87E-03	3.87E-03	3.08E-03	2.45E-03	1.95E-03	1.55E-03
144Ce	1.86E-09	2.52E-13	3.40E-17	4.60E-21	6.22E-25	8.42E-29	1.14E-32	1.54E-36	2.08E-40
147Pm	5.25E+00	3.73E-01	2.64E-02	1.88E-03	1.33E-04	9.45E-06	6.70E-07	4.76E-08	3.38E-09
151Sm	1.31E+02	1.21E+02	1.12E+02	1.04E+02	9.63E+01	8.91E+01	8.25E+01	7.64E+01	7.07E+01
152EuF	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02
154EuF	4.96E+04	2.19E+04	9.71E+03	4.30E+03	1.90E+03	8.41E+02	3.72E+02	1.65E+02	7.28E+01
204Tl	2.49E-01	3.96E-02	6.30E-03	1.00E-03	1.59E-04	2.53E-05	4.03E-06	6.41E-07	1.02E-07
210Pb	4.21E-06	3.09E-06	2.26E-06	1.66E-06	1.21E-06	8.90E-07	6.52E-07	4.78E-07	3.50E-07
227Ac	4.98E-10	3.62E-10	2.64E-10	1.92E-10	1.40E-10	1.02E-10	7.39E-11	5.38E-11	3.91E-11
Total	**7.13E+05**	**2.33E+05**	**1.13E+05**	**6.35E+04**	**3.96E+04**	**2.71E+04**	**2.02E+04**	**1.63E+04**	**1.41E+04**
Factor greater than LLW	59.4	19.4	9.4	5.3	3.3	2.3	1.7	1.4	1.2

Table 2b **Graphite Integral with the Fuel: 3yrs Dwell Time - Activity after Removal from the Reactor: Theoretical Volatile Removal**

Isotope	0yrs decay Bq/g	10 yrs decay Bq/g	20 yrs decay Bq/g	30 yrs decay Bq/g	40 yrs decay Bq/g	50 yrs decay Bq/g	60 yrs decay Bq/g	70 yrs decay Bq/g	80 yrs decay Bq/g
10Be	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01	2.15E+01
14C	2.92E+03	2.91E+03	2.91E+03	2.90E+03	2.90E+03	2.90E+03	2.89E+03	2.89E+03	2.89E+03
36Cl	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02	2.17E+02
41Ca	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01	4.53E+01
59Ni	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01	4.93E+01
79Se	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17	1.58E-17
93Zr	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06	2.09E-06
93Mo	5.66E+00	5.65E+00	5.64E+00	5.63E+00	5.62E+00	5.60E+00	5.59E+00	5.58E+00	5.57E+00
94Nb	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.65E-04	2.64E-04	2.64E-04	2.64E-04
99Tc	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01	9.18E-01
107Pd	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08	1.66E-08
126Sn	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13	2.38E-13
129I	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12	2.06E-12
135Cs	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06	1.42E-06
22Na	1.01E-01	7.02E-03	4.88E-04	3.40E-05	2.36E-06	1.64E-07	1.14E-08	7.94E-10	5.52E-11
54Mn	7.66E+03	2.30E+00	6.93E-04	2.09E-07	6.27E-11	1.89E-14	5.68E-18	1.71E-21	5.14E-25
55Fe	9.89E+04	7.59E+03	5.83E+02	4.47E+01	3.43E+00	2.63E-01	2.02E-02	1.55E-03	1.19E-04
60Co	2.24E+05	5.98E+04	1.60E+04	4.27E+03	1.14E+03	3.04E+02	8.13E+01	2.17E+01	5.80E+00
63Ni	6.22E+03	5.80E+03	5.41E+03	5.05E+03	4.71E+03	4.40E+03	4.10E+03	3.83E+03	3.57E+03
65Zn	8.68E+04	2.73E+00	8.56E-05	2.69E-09	8.43E-14	2.65E-18	8.31E-23	2.61E-27	8.20E-32
90Sr	8.78E-04	6.90E-04	5.43E-04	4.27E-04	3.35E-04	2.64E-04	2.07E-04	1.63E-04	1.28E-04
106Ru	2.28E-10	2.54E-13	2.82E-16	3.14E-19	3.49E-22	3.89E-25	4.33E-28	4.81E-31	5.35E-34
108mAg	1.20E-01	1.18E-01	1.16E-01	1.14E-01	1.12E-01	1.10E-01	1.09E-01	1.07E-01	1.05E-01
110mAg	4.99E+02	1.93E-02	7.46E-07	2.88E-11	1.12E-15	4.31E-20	1.67E-24	6.45E-29	2.49E-33
119mSn	1.15E-01	2.04E-05	3.64E-09	6.47E-13	1.15E-16	2.04E-20	3.63E-24	6.46E-28	1.15E-31
121mSn	3.11E-02	2.71E-02	2.36E-02	2.05E-02	1.79E-02	1.56E-02	1.35E-02	1.18E-02	1.03E-02
125Sb	3.86E+03	2.96E+02	2.27E+01	1.75E+00	1.34E-01	1.03E-02	7.89E-04	6.05E-05	4.65E-06
134Cs	2.73E+01	9.44E-01	3.26E-02	1.13E-03	3.90E-05	1.35E-06	4.66E-08	1.61E-09	5.57E-11
137Cs	9.70E-03	7.71E-03	6.13E-03	4.87E-03	3.87E-03	3.08E-03	2.45E-03	1.95E-03	1.55E-03
144Ce	1.86E-09	2.52E-13	3.40E-17	4.60E-21	6.22E-25	8.42E-29	1.14E-32	1.54E-36	2.08E-40
147Pm	5.25E+00	3.73E-01	2.64E-02	1.88E-03	1.33E-04	9.45E-06	6.70E-07	4.76E-08	3.38E-09
151Sm	1.31E+02	1.21E+02	1.12E+02	1.04E+02	9.63E+01	8.91E+01	8.25E+01	7.64E+01	7.07E+01
152EuF	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02	2.38E+02
154EuF	4.96E+04	2.19E+04	9.71E+03	4.30E+03	1.90E+03	8.41E+02	3.72E+02	1.65E+02	7.28E+01
204Tl	2.49E-01	3.96E-02	6.30E-03	1.00E-03	1.59E-04	2.53E-05	4.03E-06	6.41E-07	1.02E-07
210Pb	4.21E-06	3.09E-06	2.26E-06	1.66E-06	1.21E-06	8.90E-07	6.52E-07	4.78E-07	3.50E-07
227Ac	4.98E-10	3.62E-10	2.64E-10	1.92E-10	1.40E-10	1.02E-10	7.39E-11	5.38E-11	3.91E-11
Total	**4.81E+05**	**9.91E+04**	**3.53E+04**	**1.72E+04**	**1.13E+04**	**9.11E+03**	**8.11E+03**	**7.56E+03**	**7.19E+03**
Factor greater than LLW	40.1	8.3	2.9	1.4	0.9	0.8	0.7	0.6	0.6

Table 3a Permanent Core Graphite: 60yrs Dwell Time - Activity after Removal from the Reactor: Experimental Volatile Removal

Isotope	0yrs decay Bq/g	10 yrs decay Bq/g	20 yrs decay Bq/g	30 yrs decay Bq/g	40 yrs decay Bq/g	50 yrs decay Bq/g	60 yrs decay Bq/g	70 yrs decay Bq/g	80 yrs decay Bq/g
10Be	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02
14C	4.69E+05	4.68E+05	4.68E+05	4.67E+05	4.67E+05	4.66E+05	4.66E+05	4.65E+05	4.64E+05
36Cl	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03
41Ca	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03
59Ni	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02
79Se	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10
93Zr	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05
93Mo	5.07E+01	5.06E+01	5.05E+01	5.04E+01	5.03E+01	5.02E+01	5.01E+01	5.00E+01	4.99E+01
94Nb	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.31E-03	4.31E-03	4.31E-03	4.31E-03	4.31E-03
99Tc	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00
107Pd	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06
126Sn	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11
129I	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05
135Cs	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03
3H	5.14E+05	2.93E+05	1.67E+05	9.48E+04	5.40E+04	3.07E+04	1.75E+04	9.95E+03	5.66E+03
22Na	1.02E-02	7.09E-04	4.93E-05	3.43E-06	2.38E-07	1.66E-08	1.15E-09	8.02E-11	5.57E-12
54Mn	3.31E+03	9.96E-01	3.00E-04	9.01E-08	2.71E-11	8.16E-15	2.45E-18	7.38E-22	2.22E-25
55Fe	5.93E+05	4.55E+04	3.49E+03	2.68E+02	2.06E+01	1.58E+00	1.21E-01	9.30E-03	7.14E-04
60Co	3.12E+05	8.33E+04	2.23E+04	5.94E+03	1.59E+03	4.24E+02	1.13E+02	3.02E+01	8.07E+00
63Ni	1.01E+05	9.42E+04	8.79E+04	8.20E+04	7.65E+04	7.14E+04	6.66E+04	6.22E+04	5.80E+04
65Zn	2.02E+05	6.34E+00	1.99E-04	6.25E-09	1.96E-13	6.16E-18	1.93E-22	6.08E-27	1.91E-31
90Sr	9.54E-02	7.50E-02	5.90E-02	4.63E-02	3.64E-02	2.86E-02	2.25E-02	1.77E-02	1.39E-02
106Ru	2.38E-06	2.65E-09	2.95E-12	3.28E-15	3.65E-18	4.06E-21	4.51E-24	5.02E-27	5.59E-30
108mAg	3.28E-02	3.23E-02	3.17E-02	3.12E-02	3.07E-02	3.02E-02	2.97E-02	2.92E-02	2.87E-02
110mAg	2.99E+01	1.16E-03	4.47E-08	1.73E-12	6.68E-17	2.58E-21	9.99E-26	3.86E-30	1.49E-34
119mSn	3.91E+01	6.95E-03	1.24E-06	2.20E-10	3.91E-14	6.95E-18	1.24E-21	2.20E-25	3.91E-29
121mSn	1.61E-01	1.40E-01	1.22E-01	1.06E-01	9.25E-02	8.05E-02	7.01E-02	6.10E-02	5.31E-02
125Sb	2.71E+03	2.08E+02	1.60E+01	1.23E+00	9.40E-02	7.22E-03	5.54E-04	4.25E-05	3.26E-06
134Cs	1.34E+03	4.63E+01	1.60E+00	5.54E-02	1.91E-03	6.62E-05	2.29E-06	7.91E-08	2.73E-09
137Cs	2.62E-01	2.08E-01	1.66E-01	1.32E-01	1.05E-01	8.32E-02	6.61E-02	5.25E-02	4.18E-02
144Ce	1.55E-04	2.10E-08	2.84E-12	3.83E-16	5.19E-20	7.01E-24	9.49E-28	1.28E-31	1.74E-35
147Pm	3.39E+01	2.41E+00	1.71E-01	1.21E-02	8.60E-04	6.10E-05	4.33E-06	3.07E-07	2.18E-08
151Sm	2.12E+00	1.96E+00	1.82E+00	1.68E+00	1.56E+00	1.44E+00	1.34E+00	1.24E+00	1.14E+00
152EuF	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03
154EuF	1.75E+02	7.74E+01	3.43E+01	1.52E+01	6.71E+00	2.97E+00	1.31E+00	5.81E-01	2.57E-01
204Tl	6.61E+00	1.05E+00	1.67E-01	2.66E-02	4.23E-03	6.73E-04	1.07E-04	1.70E-05	2.71E-06
210Pb	1.78E-04	1.30E-04	9.56E-05	7.01E-05	5.13E-05	3.76E-05	2.76E-05	2.02E-05	1.48E-05
227Ac	2.61E-11	1.90E-11	1.38E-11	1.01E-11	7.32E-12	5.32E-12	3.87E-12	2.82E-12	2.05E-12
Total	**2.20E+06**	**9.90E+05**	**7.54E+05**	**6.56E+05**	**6.05E+05**	**5.74E+05**	**5.56E+05**	**5.43E+05**	**5.34E+05**
Factor greater than LLW	184	83	63	55	50	48	46	45	44

Table 3b Permanent Core Graphite: 60yrs Dwell Time - Activity after Removal from the Reactor: Theoretical Volatile Removal

Isotope	0yrs decay Bq/g	10 yrs decay Bq/g	20 yrs decay Bq/g	30 yrs decay Bq/g	40 yrs decay Bq/g	50 yrs decay Bq/g	60 yrs decay Bq/g	70 yrs decay Bq/g	80 yrs decay Bq/g
10Be	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02	2.25E+02
14C	1.86E+05	1.86E+05	1.86E+05	1.86E+05	1.85E+05	1.85E+05	1.85E+05	1.85E+05	1.85E+05
36Cl	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03	2.11E+03
41Ca	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03	3.08E+03
59Ni	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02	2.85E+02
79Se	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10	6.32E-10
93Zr	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05	4.95E-05
93Mo	5.07E+01	5.06E+01	5.05E+01	5.04E+01	5.03E+01	5.02E+01	5.01E+01	5.00E+01	4.99E+01
94Nb	4.32E-03	4.32E-03	4.32E-03	4.32E-03	4.31E-03	4.31E-03	4.31E-03	4.31E-03	4.31E-03
99Tc	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00	3.06E+00
107Pd	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06	3.44E-06
126Sn	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11	1.02E-11
129I	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05	1.02E-05
135Cs	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03	9.03E-03
22Na	1.02E-02	7.09E-04	4.93E-05	3.43E-06	2.38E-07	1.66E-08	1.15E-09	8.02E-11	5.57E-12
54Mn	3.31E+03	9.96E-01	3.00E-04	9.01E-08	2.71E-11	8.16E-15	2.45E-18	7.38E-22	2.22E-25
55Fe	5.93E+05	4.55E+04	3.49E+03	2.68E+02	2.06E+01	1.58E+00	1.21E-01	9.30E-03	7.14E-04
60Co	3.12E+05	8.33E+04	2.23E+04	5.94E+03	1.59E+03	4.24E+02	1.13E+02	3.02E+01	8.07E+00
63Ni	1.01E+05	9.42E+04	8.79E+04	8.20E+04	7.65E+04	7.14E+04	6.66E+04	6.22E+04	5.80E+04
65Zn	2.02E+05	6.34E+00	1.99E-04	6.25E-09	1.96E-13	6.16E-18	1.93E-22	6.08E-27	1.91E-31
90Sr	9.54E-02	7.50E-02	5.90E-02	4.63E-02	3.64E-02	2.86E-02	2.25E-02	1.77E-02	1.39E-02
106Ru	2.38E-06	2.65E-09	2.95E-12	3.28E-15	3.65E-18	4.06E-21	4.51E-24	5.02E-27	5.59E-30
108mAg	3.28E-02	3.23E-02	3.17E-02	3.12E-02	3.07E-02	3.02E-02	2.97E-02	2.92E-02	2.87E-02
110mAg	2.99E+01	1.16E-03	4.47E-08	1.73E-12	6.68E-17	2.58E-21	9.99E-26	3.86E-30	1.49E-34
119mSn	3.91E+01	6.95E-03	1.24E-06	2.20E-10	3.91E-14	6.95E-18	1.24E-21	2.20E-25	3.91E-29
121mSn	1.61E-01	1.40E-01	1.22E-01	1.06E-01	9.25E-02	8.05E-02	7.01E-02	6.10E-02	5.31E-02
125Sb	2.71E+03	2.08E+02	1.60E+01	1.23E+00	9.40E-02	7.22E-03	5.54E-04	4.25E-05	3.26E-06
134Cs	1.34E+03	4.63E+01	1.60E+00	5.54E-02	1.91E-03	6.62E-05	2.29E-06	7.91E-08	2.73E-09
137Cs	2.62E-01	2.08E-01	1.66E-01	1.32E-01	1.05E-01	8.32E-02	6.61E-02	5.25E-02	4.18E-02
144Ce	1.55E-04	2.10E-08	2.84E-12	3.83E-16	5.19E-20	7.01E-24	9.49E-28	1.28E-31	1.74E-35
147Pm	3.39E+01	2.41E+00	1.71E-01	1.21E-02	8.60E-04	6.10E-05	4.33E-06	3.07E-07	2.18E-08
151Sm	2.12E+00	1.96E+00	1.82E+00	1.68E+00	1.56E+00	1.44E+00	1.34E+00	1.24E+00	1.14E+00
152EuF	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03	8.21E-03
154EuF	1.75E+02	7.74E+01	3.43E+01	1.52E+01	6.71E+00	2.97E+00	1.31E+00	5.81E-01	2.57E-01
204Tl	6.61E+00	1.05E+00	1.67E-01	2.66E-02	4.23E-03	6.73E-04	1.07E-04	1.70E-05	2.71E-06
210Pb	1.78E-04	1.30E-04	9.56E-05	7.01E-05	5.13E-05	3.76E-05	2.76E-05	2.02E-05	1.48E-05
227Ac	2.61E-11	1.90E-11	1.38E-11	1.01E-11	7.32E-12	5.32E-12	3.87E-12	2.82E-12	2.05E-12
Total	**1.41E+06**	**4.15E+05**	**3.05E+05**	**2.80E+05**	**2.69E+05**	**2.63E+05**	**2.58E+05**	**2.53E+05**	**2.48E+05**
Factor greater than LLW	117	35	25	23	22	22	21	21	21

Table 4a Measured AVR Graphite Specific Activities for Selected Isotopes: Prior to Treatment

Radionuclide	Total Reflector Graphite Activity Bq	Mass of Reflector Graphite (g)	Specific Activity of the Reflector Graphite (Bq/g)	Total Isolation Carbon Activity Bq	Mass of Isolation Carbon (g)	Specific Activity of Isolation Carbon (Bq/g)
3H	8.8E14	6.7E7	1.31E7	6.9E15	1.58E8	4.4E7
14C	4.6E12	6.7E7	6.9E4	2.9E14	1.58E8	1.8E6
36Cl	1.5E9	6.7E7	2.2E1	5.9E10	1.58E8	3.7E2
63Ni	4.1E12	6.7E7	6.1E4	8.5E12	1.58E8	5.4E4

Table 4b Measured AVR Graphite Specific Activities for Selected Isotopes: Experimental Volatile Removal

Radionuclide	Specific Activity of the Reflector Graphite (Bq/g)	Specific Activity of Isolation Carbon (Bq/g)
3H	4.0E6	1.3E7
14C	5.3E4	1.4E6
36Cl	2.2E1	3.7E2
63Ni	6.1E4	5.4E4

Table 4c Measured AVR Graphite Specific Activities for Selected Isotopes: Theoretical Volatile Removal

Radionuclide	Specific Activity of the Reflector Graphite (Bq/g)	Specific Activity of Isolation Carbon (Bq/g)
3H	0	0
14C	2.1E4	5.5E5
36Cl	2.2E1	3.7E2
63Ni	6.1E4	5.4E4

Figure 1 **Replaceable Reflector Graphite: 6yrs Dwell Time – Main Contributors to Activity after Removal from the Reactor: Experimental Volatile Removal**

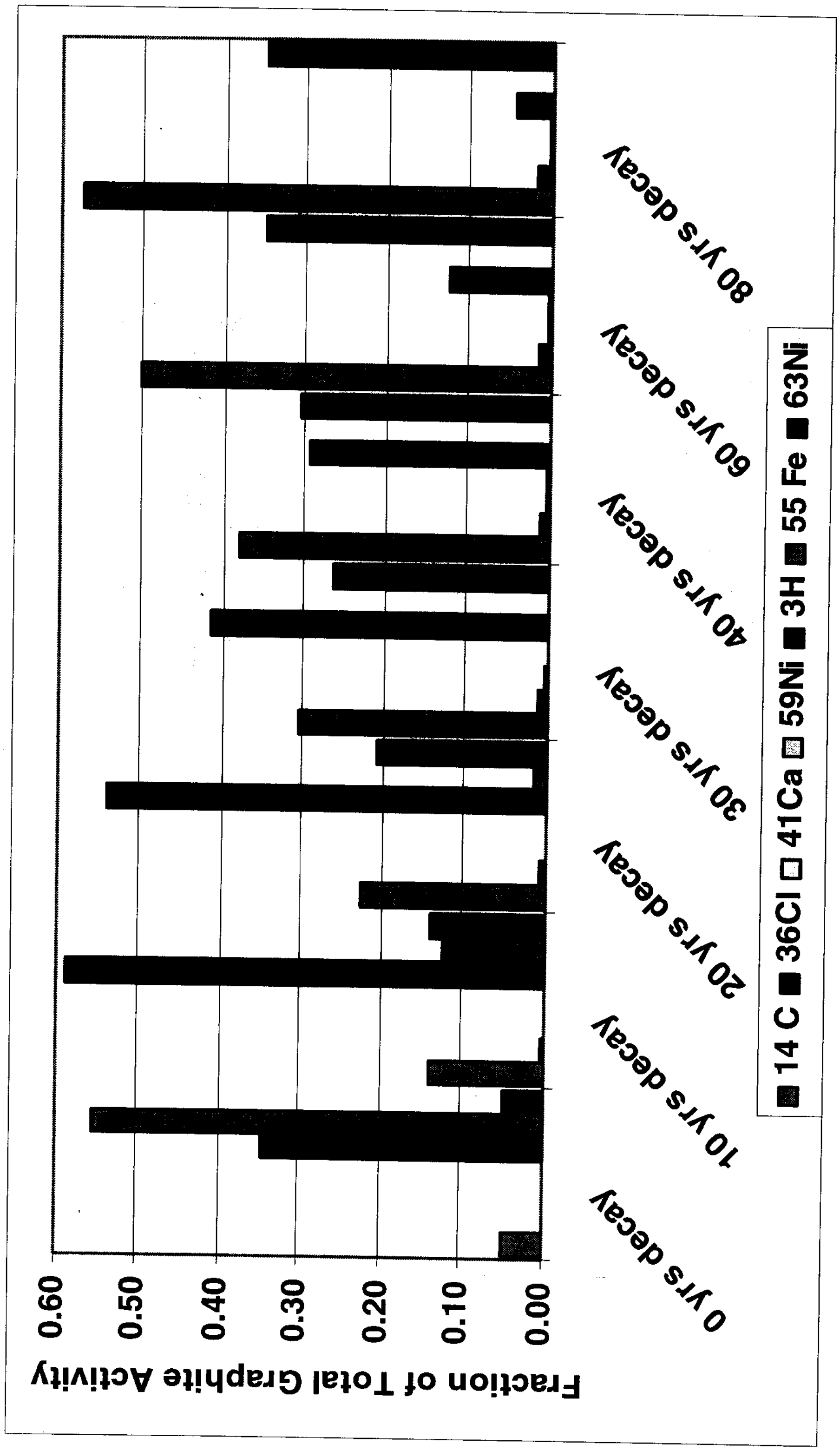

Figure 2 Replaceable Reflector Graphite: 6yrs Dwell Time – Main Contributors to Activity after Removal from the Reactor: Theoretical Volatile Removal

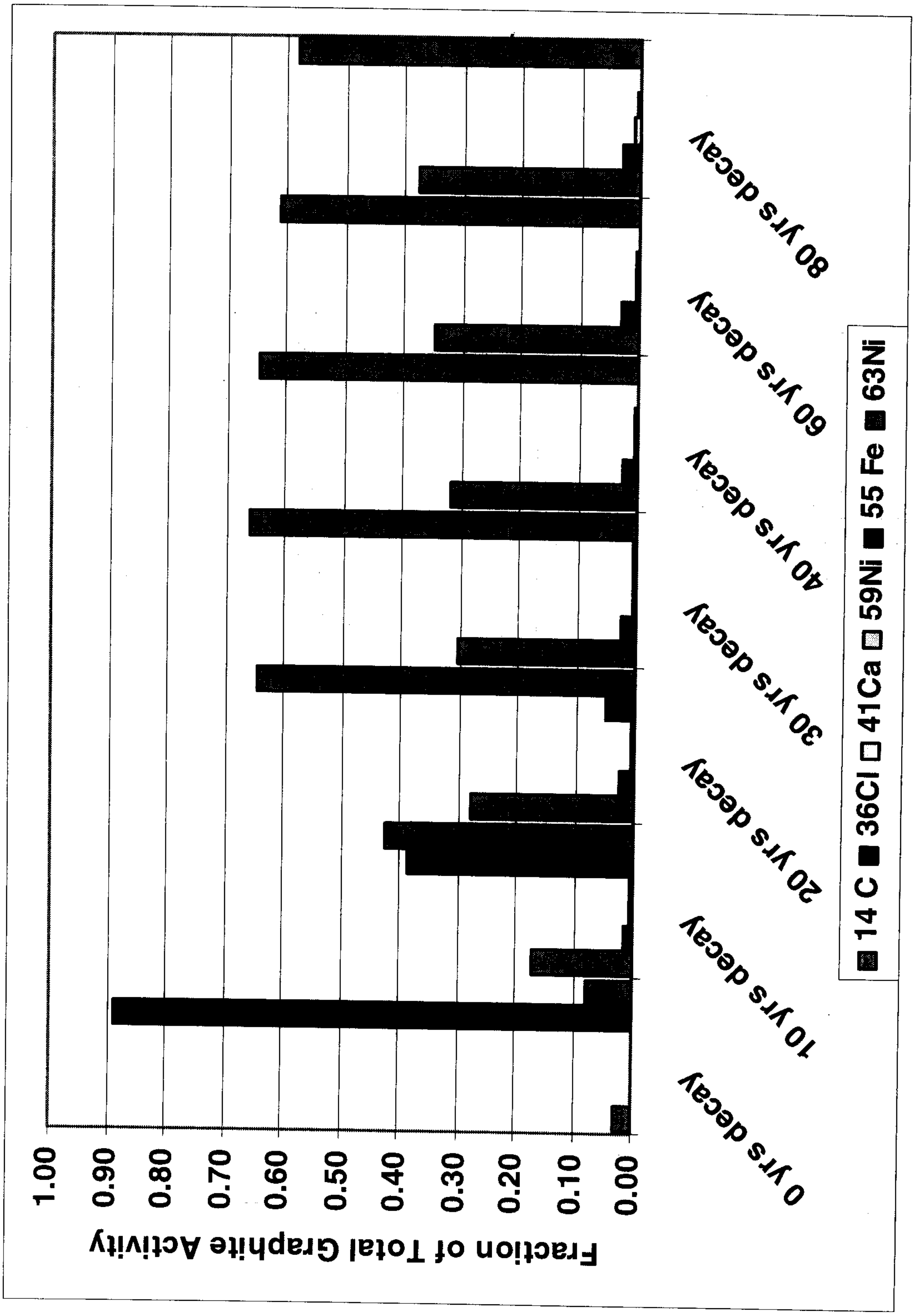

Figure 3 **Graphite Integral with the Fuel 3yrs Dwell Time – Main Contributors to Activity after Removal from the Reactor: Experimental Volatile Removal**

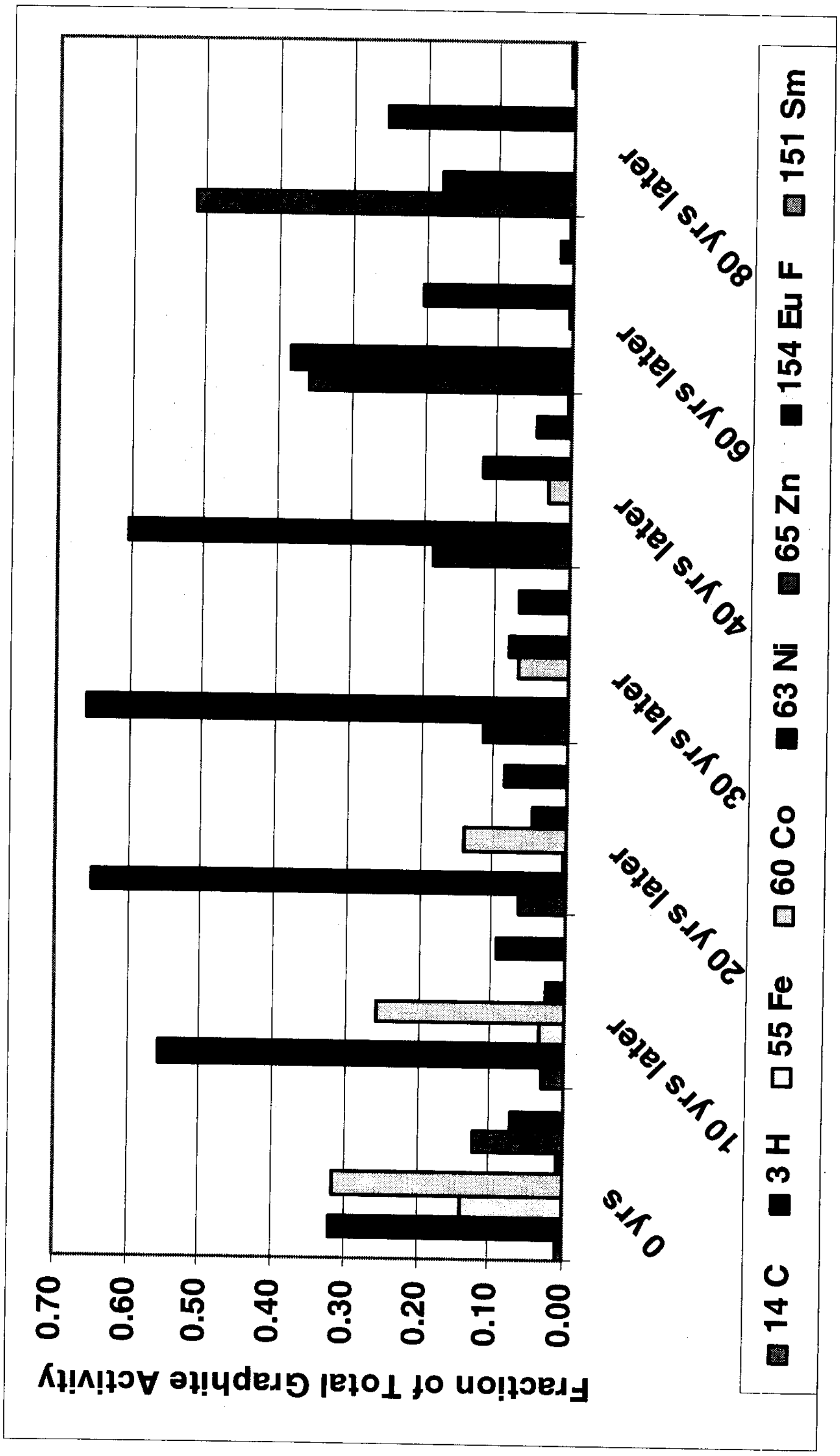

Figure 4 **Graphite Integral with the Fuel 3yrs Dwell Time – Main Contributors to Activity after Removal from the Reactor: Theoretical Volatile Removal**

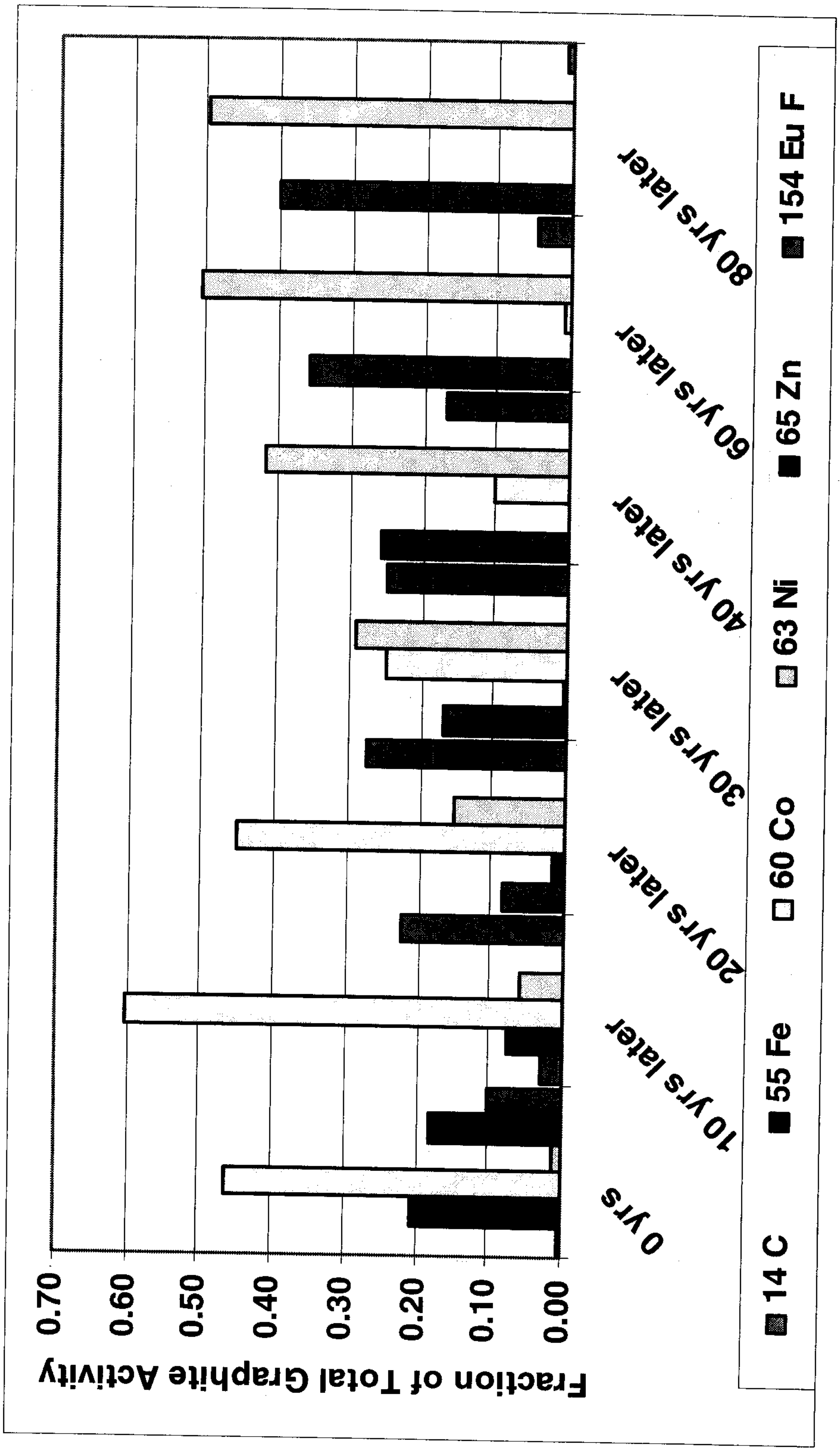

Figure 5 **Permanent Core Graphite: 60yrs Dwell Time - Activity after Removal from the Reactor: Experimental Volatile Removal**

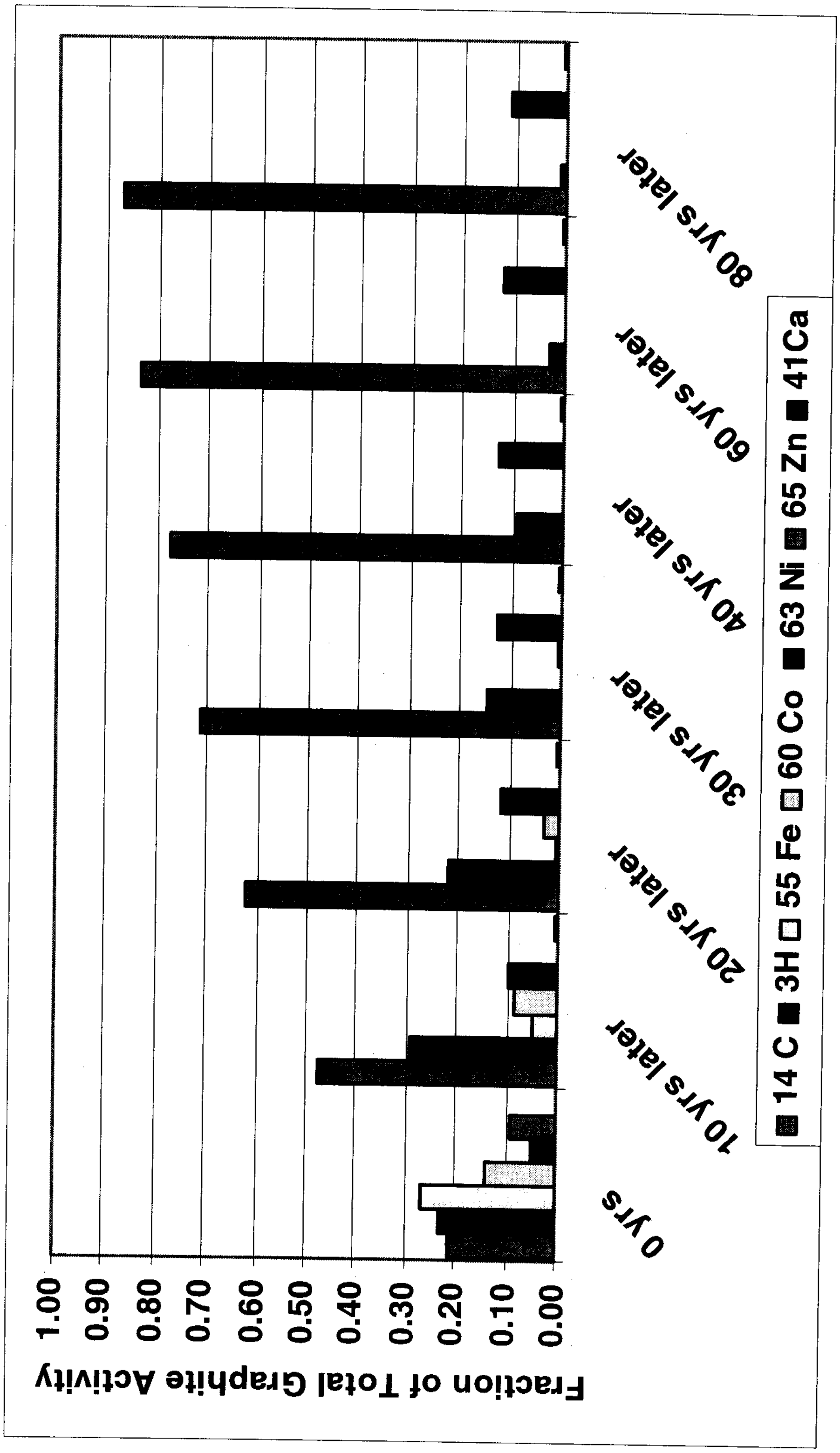

Figure 6 Permanent Core Graphite: 60yrs Dwell Time - Activity after Removal from the Reactor: Theoretical Volatile Removal