

THE EFFECTS OF IMPURITIES ON THE ACTIVATION OF SiC, VANADIUM AND FERRITIC ALLOYS. H. Attaya and D. Smith (Argonne National Laboratory)

OBJECTIVE

The objective of this work is to assess the impact of the trace elements on the activation of the leading reduced activation candidate materials for fusion reactors. The materials considered in this work are the V4Cr4Ti vanadium alloy, the 9Cr2WVTa ferritic alloy, and the silicon carbide (SiC).

SUMMARY

Consistent transport and activation calculations have been performed to compare the activation responses of the leading reduced-activation materials in a fusion power reactor. Another set of calculations has been made to evaluate the effects of the trace elements on these responses. The materials considered in this work are the V4Cr4Ti vanadium alloy, the 9Cr2WVTa ferritic alloy, and the silicon carbide (SiC). In addition, calculations have also been made for the conventional 316SS and HT-9 alloys. The TPSS conceptual design has been utilized in this work. The results show that the V4Cr4Ti alloy has the minimum operational and the minimum long-term radioactivity and decay heat. The SiC has the minimum intermediate-term radioactivity. The effects of impurities are noticed with respect to the V4Cr4Ti and SiC. With respect to the 9Cr2WVTa, the impurities have small effects.

INTRODUCTION

The selection of structural materials for fusion reactors is influenced by the activation responses of these materials. The activation response of any material, in turn, is affected by the composition of this material and equally important by the neutron spectrum seen by the material. The neutron spectrum itself depends strongly on the materials' compositions in and around any particular region in a reactor. Thus there is a direct and strong dependency of the activation responses of a material on the design of the reactor in which it is used. This fact is often overlooked and most of the time a single spectrum is used to evaluate the activation responses of different materials.

In this work, we have utilized the tokamak power system study (TPSS) reactor design¹ to evaluate the activation responses of the V4Cr4Ti vanadium alloy, the 9Cr2WVTa ferritic alloy, the silicon carbide (SiC), and the conventional 316SS and HT-9 alloys. This design is based on the self-cooled lithium-vanadium concept and uses natural lithium in the first wall (FW), the breeder, and the reflector. The structural material (SM), the V15Cr5Ti alloy, is used only in these regions. The FW is 1 cm thick and has equal volume fractions of Li and SM. In these calculations, we assume 5 MW/m² neutron wall loading and 5 years of operation i.e., 25 MWa/m² neutron fluence.

It should be emphasized that changing the structural material of a design would require optimizing the design for that material and may result in a completely different design. This optimization is beyond the scope of the present work. Nevertheless, the consistent transport and activation provides a reasonable comparison of the different structural materials.

ALLOYS' COMPOSITIONS AND NEUTRON FLUX

Table 1 shows the weight and the atomic compositions of the alloys used in this work. The weight fractions and the atomic fractions of the elements are given in percentage or in ppm. The fractions given in ppm are preceded by *. The V4Cr4Ti impurity content is based on chemical analyses of different heats of similar alloys. The SiC composition is assumed stoichiometric and its impurities are partially taken from Ref. 2. The impurities of the ORNL 9Cr2WVTa ferritic steel are assumed as that of the modified HT-9³.

The neutron fluxes in the TPSS FW, for each SM, have been calculated by the transport code ONEDANT⁴ and are shown in Fig. 1. In this figure, the neutron flux of the V4Cr4Ti case is shown in absolute values (right scale) and the other SMs' fluxes are shown relative to V4Cr4Ti's flux (left scale). It is clear that there are large differences in the neutron fluxes among the different SMs. For example, the SiC's thermal flux is more than two orders of magnitude higher than the V4Cr4Ti's thermal flux. This also indicates the necessity of consistent transport and activation calculations.

ACTIVATION OF PURE ALLOYS

The activation code RACC^{5,6} has been used in the activation calculations together with the neutron cross-section library EAF3⁷. Consider first the reduced activation materials V4Cr4Ti, SiC, and 9Cr2WVTa, without impurities. Figure 2 shows the radioactive inventories of these materials and for the conventional materials HT9 and 316SS after 25 MWA/m² neutron fluence. The decay heat generation rates and the point-source contact doses of these materials are shown in Figs. 3 and 4, respectively. During operation and at shutdown, the V4Cr4Ti alloy has the least radioactive inventory, the least decay heat, and the least contact dose. After less than an hour after shutdown, these activation responses of the SiC became the least compared to those of the other SMs, and with large difference, and remain as such for about ten years. Afterward, the V4Cr4Ti's responses became the lowest. It can be also noticed that there are small differences between the activation responses of the 9Cr2WVTa alloy and those of the conventional HT9 alloy for about ten years after shutdown.

EFFECTS OF IMPURITIES

The V4Cr4Ti alloy contains 0.05 wt% Si which generates the long-lived isotope ²⁶Al. Other impurities in this alloy are capable of producing long-lived isotopes such as ¹⁴C (from N and O), ⁵⁹Ni (from Ni), ⁹⁹Tc and ⁹⁴Nb (from Mo and Nb). Figure 5 shows the radioactive inventories of the pure alloy with and without Si and with the full composition listed in Table. 1.

Figure 6 shows the effects of the impurities in the case of SiC. In this case also, more ¹⁴C is produced by N and O and this isotope dominates the SiC radioactivity after 10 years and for about 10000 years. The isotope ⁵⁵Fe (from Fe) dominates the radioactivity from one week after shutdown and for few years afterward. The very long-term radioactivity is due to C (¹⁰Be) and Si (²⁶Al).

Figure 7 shows the effects of the impurities on the 9Cr2WVTa alloy and shows also the radioactivity of the conventional HT9 alloy. The impurities in this case do not make a substantial difference since most of the radioactivity comes from Fe, Mn, and W. Adding Ni and Cu to this alloy results in the increase of the radioactivity at about 100 years.

CONCLUSIONS

Consistent transport and activation calculations have been performed to compare the activation responses of the leading reduced-activation materials in a fusion power reactor. Another set of calculations has been made to evaluate the effects of the trace elements on these responses. The materials considered in this work are the V4Cr4Ti vanadium alloy, the 9Cr2WVTa ferritic alloy, and the silicon carbide (SiC). In addition, calculations have also been made for the conventional 316SS and HT-9 alloys. The TPSS conceptual design has been utilized in this work. The results show that the V4Cr4Ti alloy has the minimum operational and the minimum long-term radioactivity and decay heat. The SiC has the minimum intermediate-term radioactivity. The effects of impurities are noticed with respect to the V4Cr4Ti and SiC. With respect to the 9Cr2WVTa, the impurities have small effects

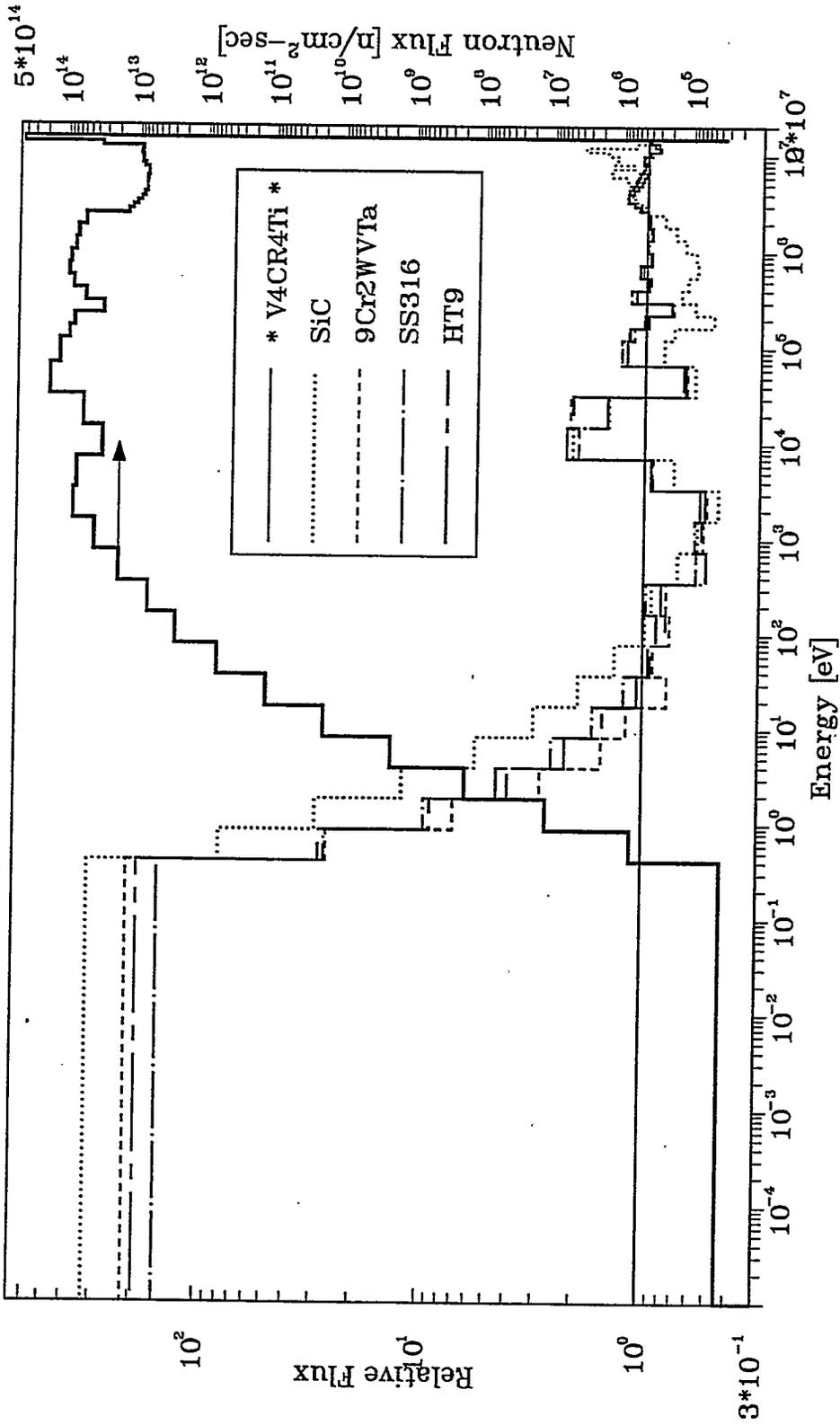
Table 1. The weight and atomic compositions of the different alloys in percentage or in wppm/appm (marked by *).

	V4CR4Ti		SiC		9Cr2WVTa		HT9		316SS	
	gm/cc	a-b/cc ^a	gm/cc	a-b/cc	gm/cc	a-b/cc	gm/cc	a-b/cc	gm/cc	a-b/cc
den.	6.1	7.234-2 ^b	3.217	9.762-2	7.8	8.401-2	7.8	8.531-2	7.855	8.503-2
	% or wppm(*)	% or appm(*)	% or wppm(*)	% or appm(*)	% or wppm(*)	% or appm(*)	% or wppm(*)	% or appm(*)	% or wppm(*)	% or appm(*)
B					*10.00	*51.72	0.01	0.05		
C	*50.00	0.02	28.74	47.48	0.1	0.47	0.2	0.92		
N	0.01	0.04	*620.00	0.09	*10.00	*39.92	0.05	0.2		
O	0.02	0.06	3.98	4.94	*70.00	0.02	0.01	0.03		
Na			*12.00	*10.36						
Al	0.01	0.02	*25.00	*18.39	*80.00	0.02	0.01	0.02	0.3	0.62
Si	0.05	0.09	67.2	47.48	0.2	0.4	0.35	0.69	0.46	0.91
P	*30.00	*49.19			0.01	0.02	0.02	0.04		
S	*10.00	*15.84			*40.00	*69.75	0.02	0.03		
Cl	*0.20	*0.29								
K	*0.10	*0.13	*8.00	*4.06	*3.00	*4.29	*3.00	*4.22		
Ti	4	4.24	*8.00	*3.32	0.1	0.12	0.09	0.1	0.04	0.05
V	91.9	91.61			0.25	0.27	0.3	0.32		
Cr	4	3.91	*30.00	*11.45	9	9.68	12	12.71	17.1	18.3
Mn					0.45	0.46	0.55	0.55	1.7	1.72
Fe	*40.00	*36.37	*130.00	*46.20	87.78	87.88	84.16	82.98	64.57	64.33
Co					*50.00	*47.44	0.02	0.02	0.03	0.03
Ni	*4.00	*3.46	*18.00	*6.09	*60.00	*57.16	0.5	0.47	13.2	12.51
Cu	*1.00	*0.80			*30.00	*26.40	0.09	0.08	0.1	0.09
As	*0.10	*0.07								
Zr					*10.00	*6.13	*10.00	*6.04		
Nb	*1.00	*0.55			*1.10	*0.66	0.11	0.07		
Mo	*4.00	*2.12			*2.70	*1.57	1	0.57	2.5	1.45
Ag					*0.90	*0.47	*1.00	*0.51		
Cd					*1.00	*0.50	*1.00	*0.49		
Sn					*30.00	*14.13	*30.00	*13.91		
Sb					*5.00	*2.30	*10.00	*4.52		
Ba					*2.00	*0.81	*10.00	*4.01		
Tb					*2.00	*0.70	*5.00	*1.73		
Ta	*2.00	*0.56			0.07	0.02	*10.00	*3.04		
W	*2.00	*0.55			2	0.61	0.5	0.15		
Ir					*2.00	*0.58	*5.00	*1.43		
Pb					*5.00	*1.35	*10.00	*2.66		
Bi					*2.00	*0.54	*10.00	*2.63		

* = wppm or appm, shaded numbers are the major constituents.

(a) atomic density in atoms-barn/cc, barn=10⁻²⁴

(b) reads as 7.234 × 10⁻².



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Figure 1. The neutron flux in the FW for the vanadium case (right axis). Other fluxes are shown relative the vanadium flux (left axis).

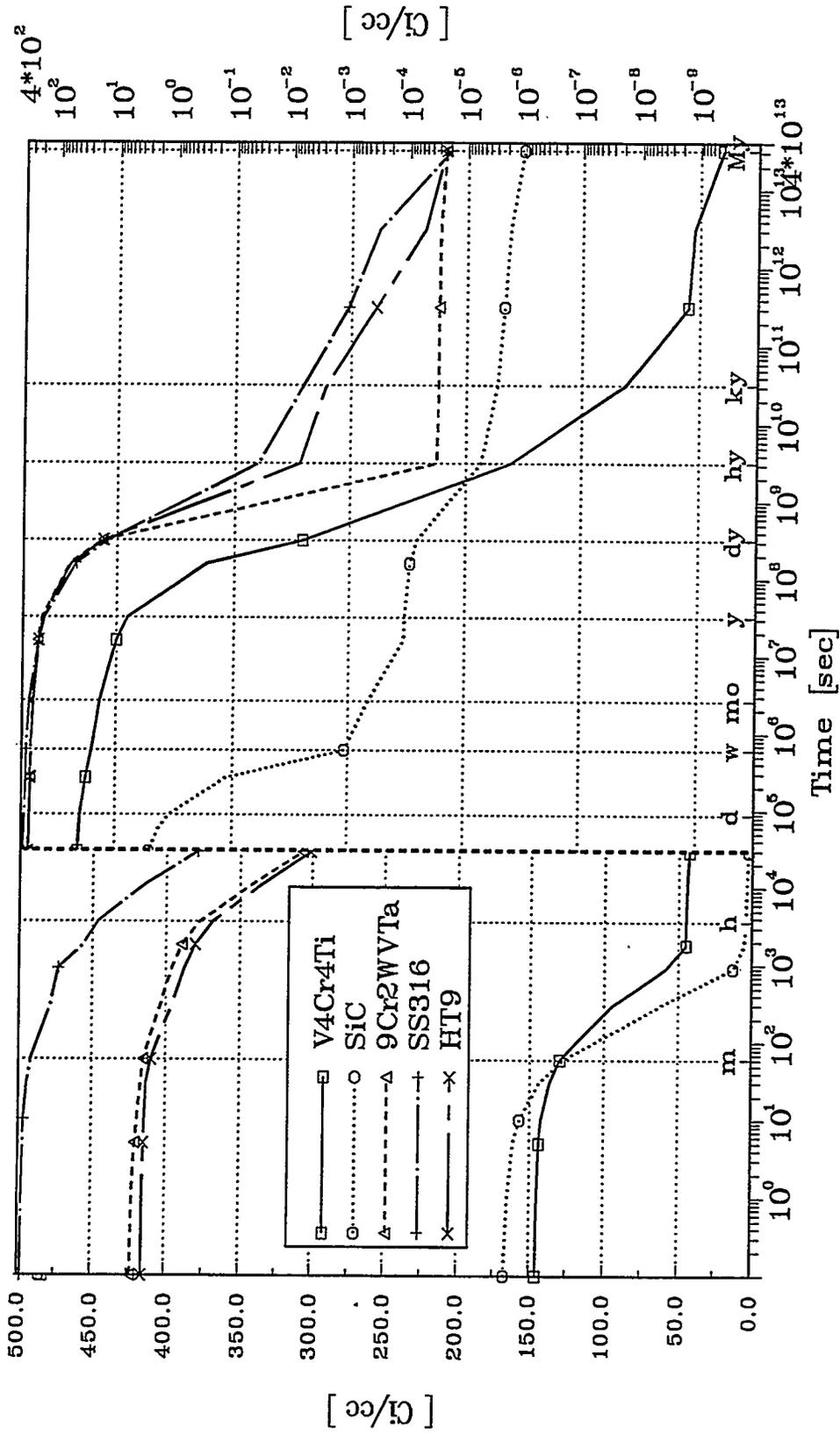


Figure 2. The radioactive inventories of the different SMs after shutdown. The short-term radioactive inventories are shown in linear scale (left) and the long-term radioactive inventories are shown in logarithmic scale (right).

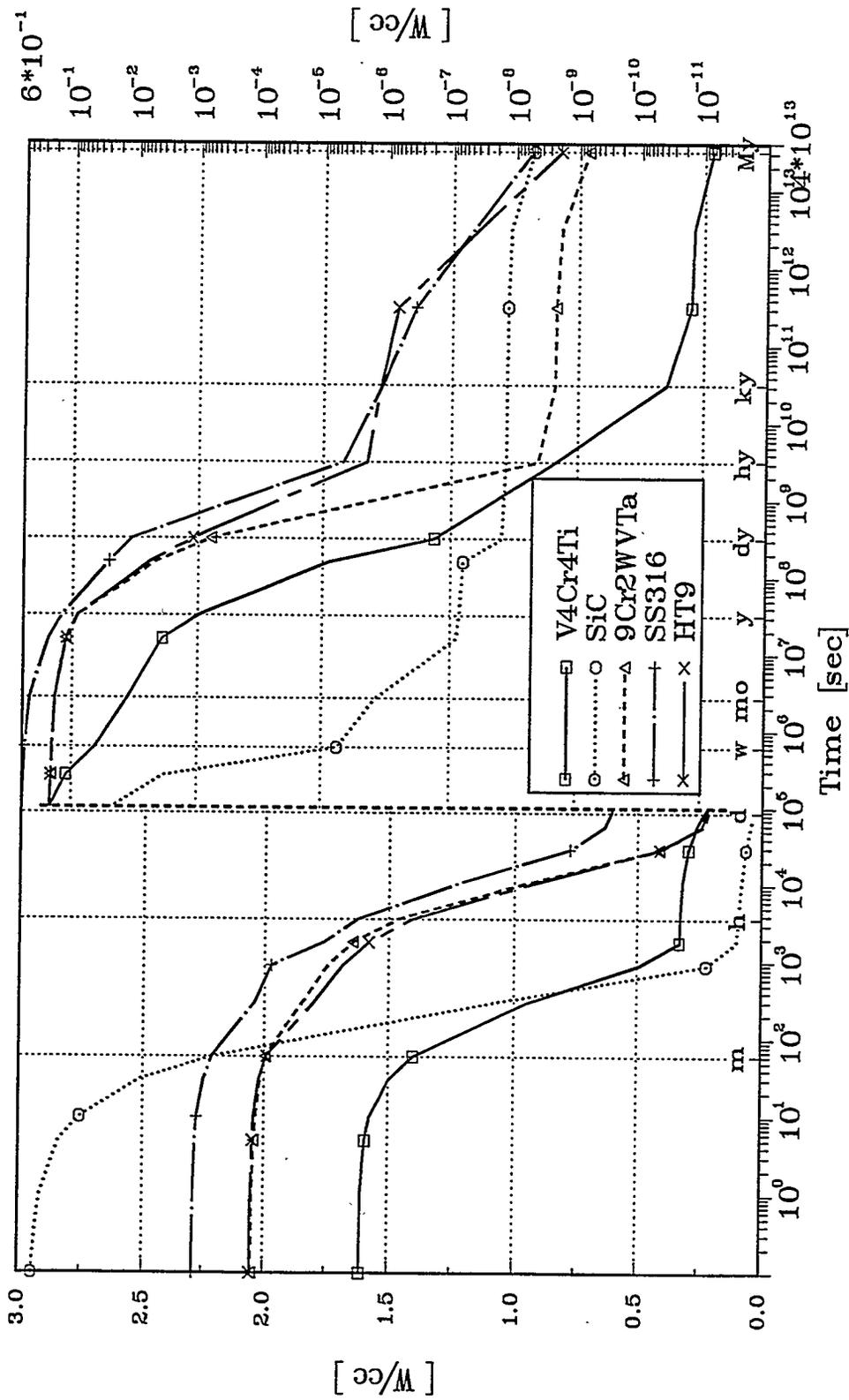


Figure 3. The decay heat generation rates of the different SMs after shutdown.

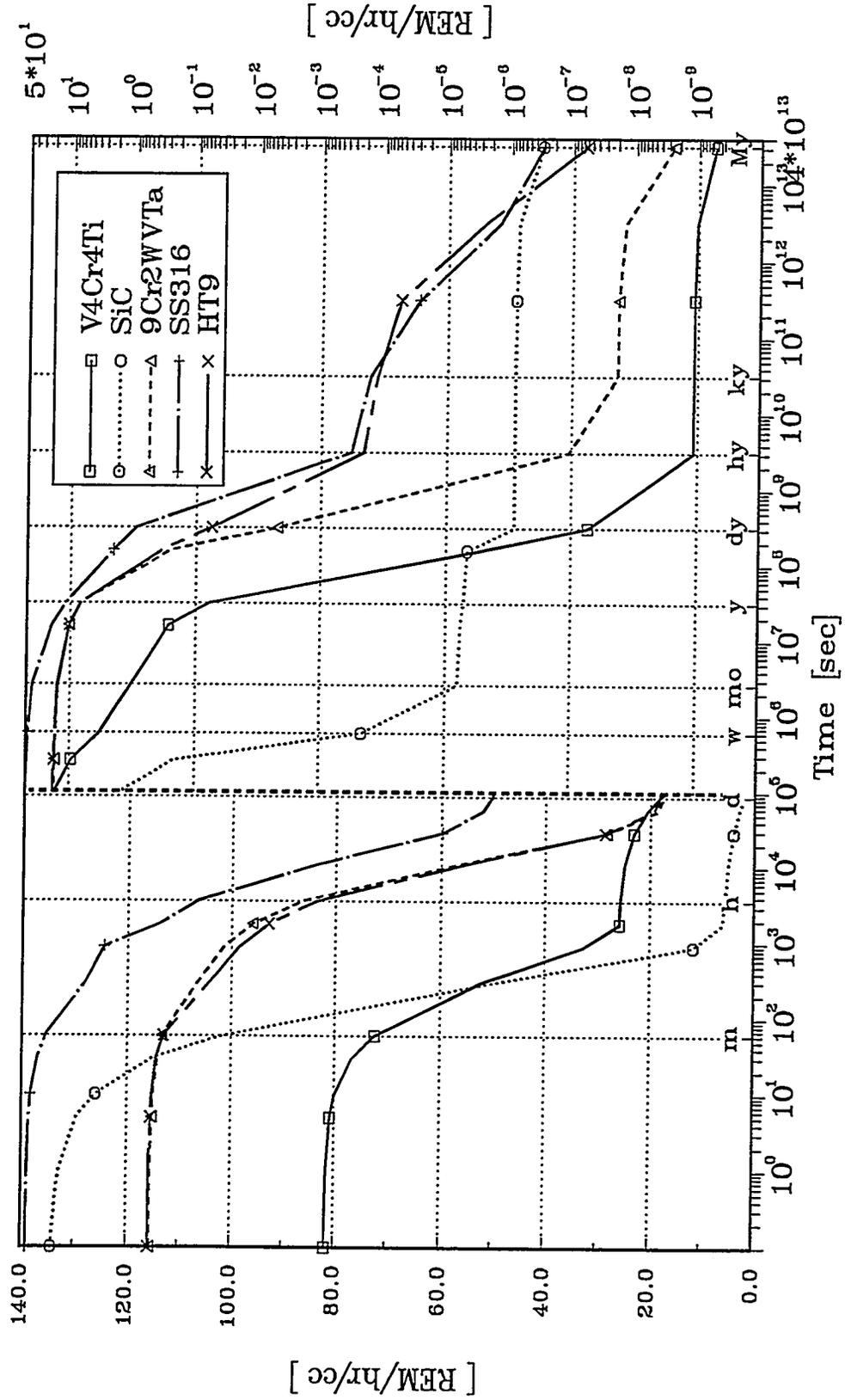


Figure 4. The point-source contact dose of the different SMs.

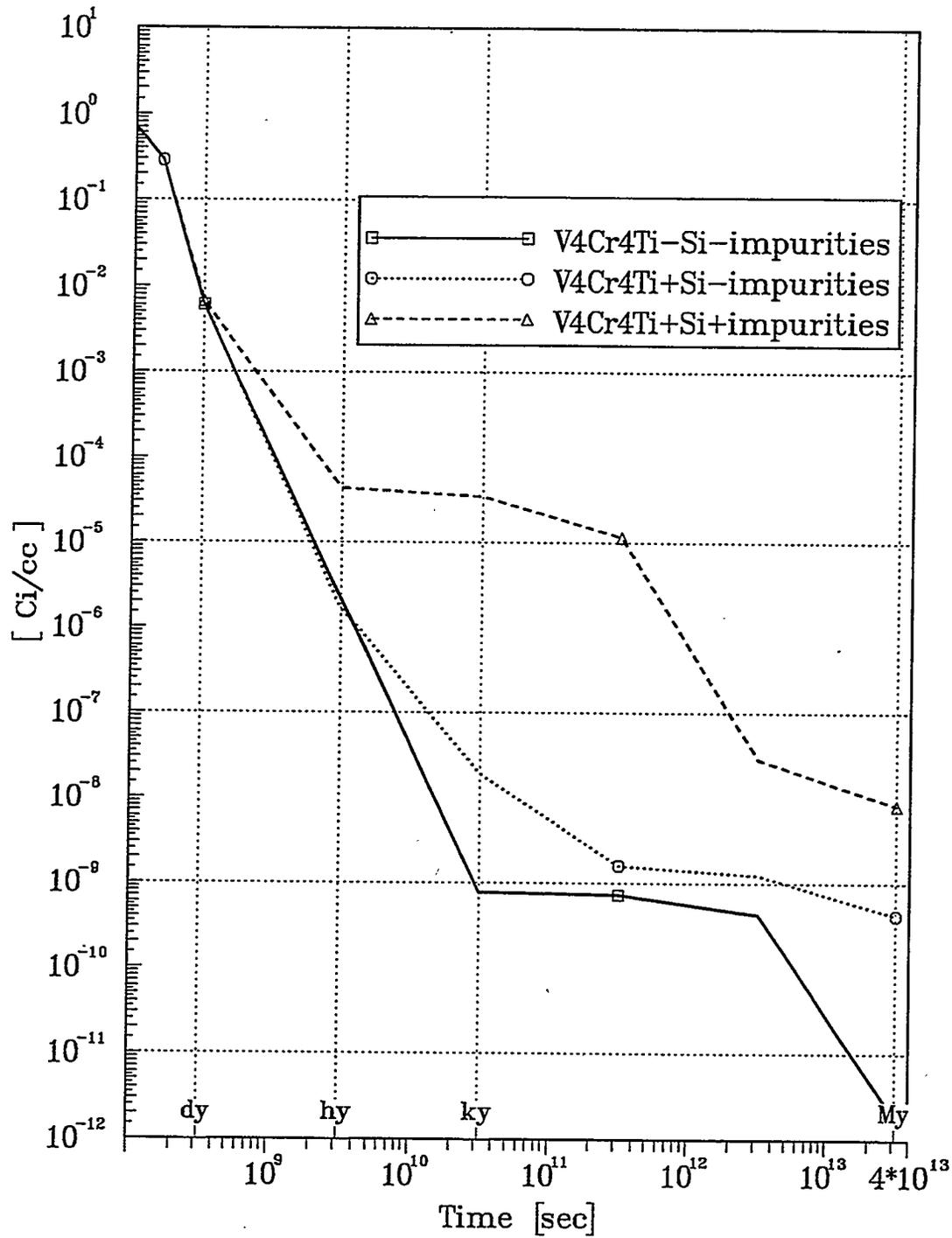


Figure 5 . The radioactivity of the V₄Cr₄Ti alloy, with only V, Cr, Ti, with Si included, and with the full composition in Table 1

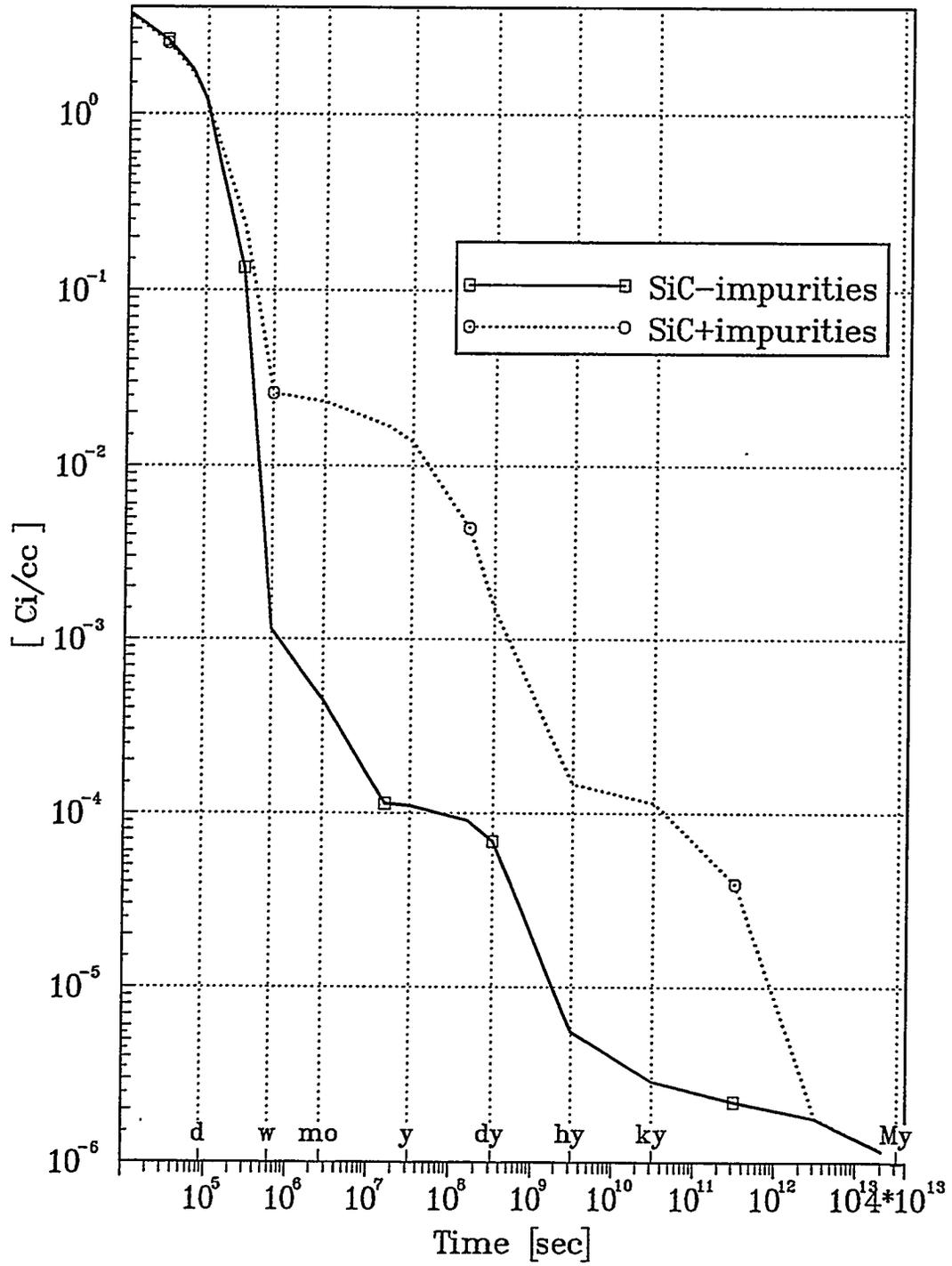


Figure 6. The radioactivity of SiC with and without impurities.

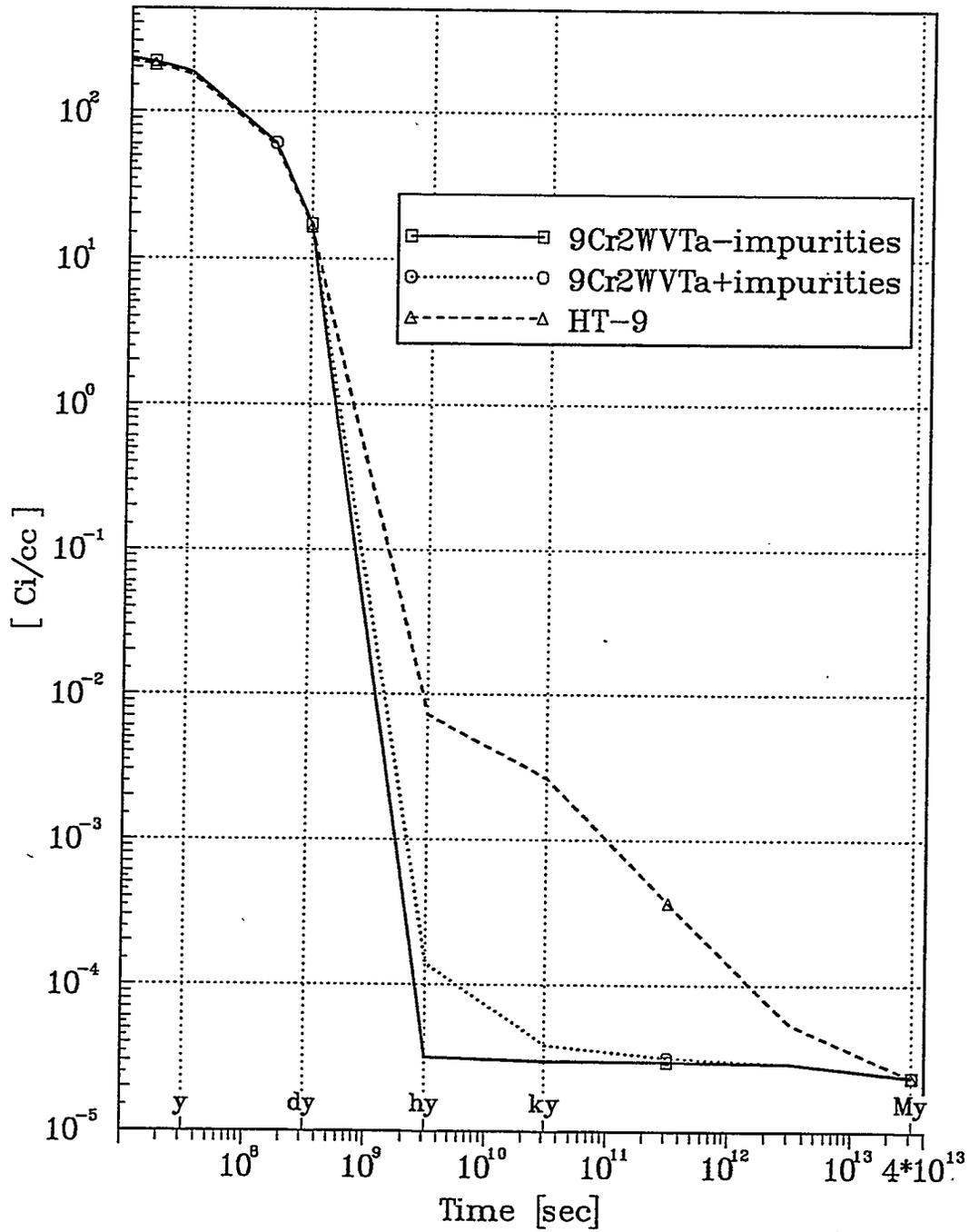


Figure 7. The radioactivity of HT9 and 9Cr2WVTa with and without impurities.

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