

Vanadium Irradiation at ATR - Neutronics Aspects - Itacil C. Gomes and Dale L. Smith (Argonne National Laboratory)

SUMMARY

Calculations were performed to estimate damage and transmutation rates in vanadium irradiated in the ATR (Advanced Test Reactor) located in Idaho. The main focuses of the study are to evaluate the transmutation of vanadium to chromium and to explore ways to design the irradiation experiment to avoid excessive transmutation. It was found that the A-hole of ATR produces damage rate of ~ 15-30 dpa/full power year with a transmutation rate of ~ 0.2%/dpa of vanadium to chromium. A thermal neutron filter can be incorporated into the design to reduce the vanadium-to-chromium transmutation rate to low levels. A filter 1-2 mm thick of gadolinium or hafnium can be used.

ATR Reactor

The Idaho National Engineering Laboratory's Advanced Test Reactor has a nominal full power output of 250 MW [1]. The reactor is composed basically of five nearly independent lobes which can operate at different power levels from each other during the same cycle. The nominal power of each lobe is 50 MW but power shifting allows a maximum lobe power of 60 MW - a minimum lobe power of 17 MW and the other lobes in between, producing a total power of 250 MW. Several irradiation holes are provided, with a variety of dimensions and neutron energy spectra. The vertical neutron flux distribution is relatively flat over a large portion of the height of the core (~70-80 cm of the ~120 cm core) which allows a larger active length of the irradiation capsule compared to other test reactors. This study focuses primarily on the A-10 hole position of the reactor; however, the numbers derived here can also be applied to holes which have a similar neutron energy spectrum to this particular hole.

Damage and Transmutation Rates

Despite having a nominal power level of 250 MW the ATR reactor has typically been operating at 125 MW [2]. The lobe in which the A-10 hole is located, in this operating scenario, has a power of 30 MW. Figure 1 shows the neutron energy spectrum at the A-10 hole. Table 1 presents the breakdown between fast and thermal neutron flux at this position compared with the HFIR (High Flux Irradiation Reactor) RB* position with and without hafnium cover (3mm thick).

Table 1. Breakdown of the neutron flux between fast and thermal components.

	ATR A-10	HFIR/RB*	HFIR/RB* with Hf
Fast (E>0.1MeV)	5.4×10^{14}	4.5×10^{14}	4.5×10^{14}
Thermal (E<1eV)	2.6×10^{14}	8.5×10^{14}	1.0×10^{14}

As one can notice from Table 1, the fast-to-thermal ratio in the A-10 hole is larger than the HFIR/RB* without using any thermal neutron filter. In terms of fusion materials irradiation testing, this ratio must be large to better simulate a fusion environment. The fast-to-thermal ratio in a first wall of a fusion device is typically larger than 30 and may even higher for some blanket concepts.

The calculated damage rate for the A-10 hole is 15 dpa/year for vanadium at a lobe power level of 30 MW. (It would be 30 dpa/fpy if one considers 60 MW). This damage rate can be compared with the HFIR/RB* position which produces a damage rate of 9 dpa/fpy for vanadium.

Figure 2 displays the variation of the chromium concentration in the V4Cr4Ti alloy as a function of the damage rate (dpa) for several reactors. These calculations indicate that the transmutation rate for ATR without any thermal neutron filter is considerably less than the RB* position of HFIR. Similar calculations for vanadium transmutations in the core-edge region of the SM-3 reactor (Russian reactor) are based on two different sources of information. The high value (0.3%/dpa) is based on the Russian calculation for the transmutation rate, whereas the lower rate (0.11%/dpa) is based on U.S. calculations using a neutron energy spectrum provided by the Russians. There remain high uncertainties in the actual values for the SM-3 reactor.

Normalized Neutron Energy Spectrum for the ATR, HFIRrb*,rbh
Neutron flux per unit lethargy as a Function of the Energy

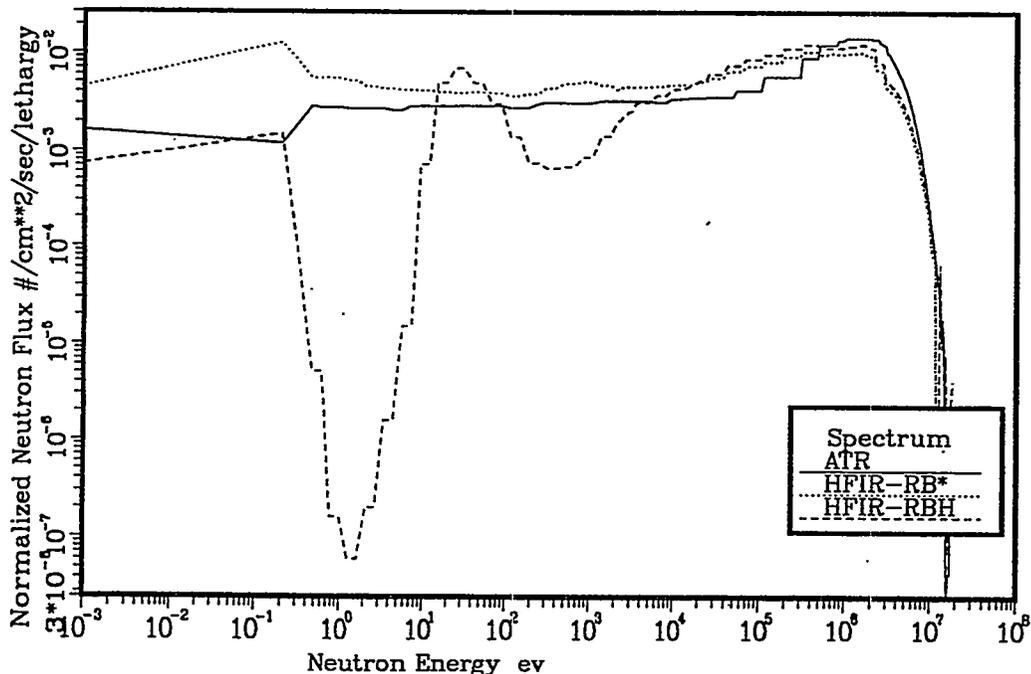


Figure 1. Normalized neutron energy spectrum for the A-10 hole of the ATR reactor.

Transmutation of V4Cr4Ti at Different Facilities
ATR-core, HFIR-RBH, HFIR-RB4, SM-3:core, STARFIRE, ITER, EBR

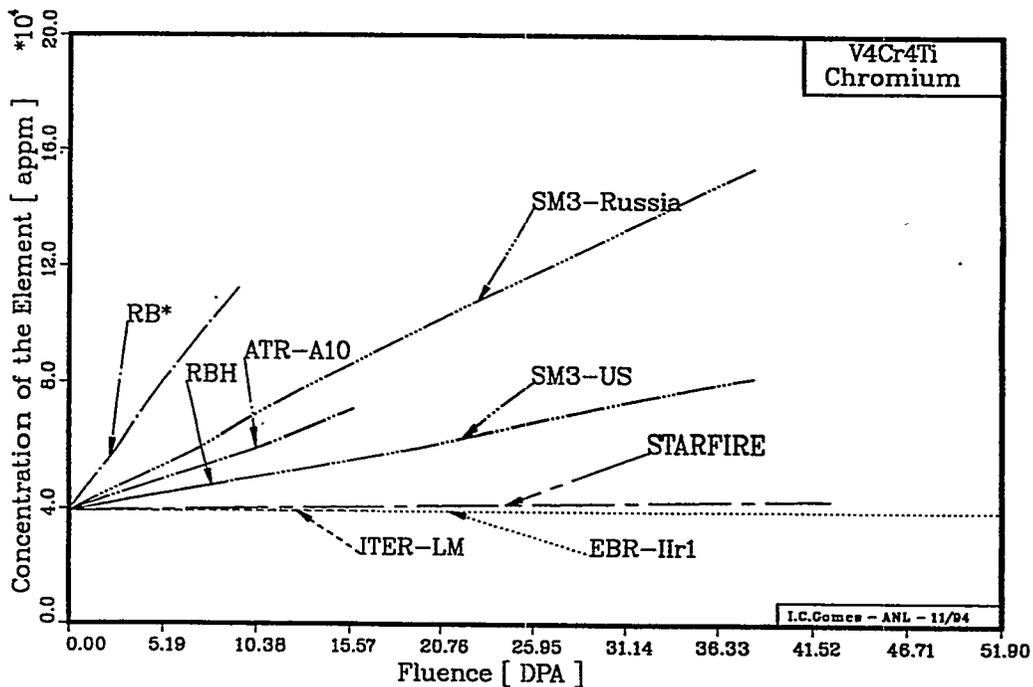


Figure 2. Variation of the chromium concentration in the V4Cr4Ti alloy for different neutron environments as a function of the fluence (dpa).

Thermal Neutron Filter

The transmutation of the elements in an alloy during irradiation testing should be compatible with that expected in the proposed operating environment, otherwise the post-irradiation test would be performed on a material with different compositional characteristics than that for the projected application. Vanadium has a significant transmutation cross-section (5 barns) at the thermal neutron energy region [$^{51}\text{V}(n, \gamma) ^{52}\text{V} \rightarrow T 1/2 = 3.7 \text{ min.} \rightarrow ^{52}\text{Cr}$]. Under high thermal neutron flux irradiation, transmutation rates up to 1%/dpa increase in the chromium content can be expected. For a typical fusion reactor first wall-spectrum, this transmutation rate is very low. This is also the case for fast fission reactor irradiations. To avoid significant changes in the composition of the vanadium alloys during irradiation in water cooled fission test reactors, the use of thermal neutron absorbers (or filters) is recommended in most of the cases.

In this section we analyze a few possible thermal neutron filters, including Hf, Cd, Gd and B₄C. Figure 3 displays a comparison of the performance of these filters without accounting for the burnup of the absorber atoms (assuming that the filter layer is thick enough to survive the full irradiation time represented). As one can see, Gd, Cd, and B₄C present a very good performance in absorbing the thermal neutrons and reducing the transmutation rate of vanadium. Hafnium reduces the transmutation rate by more than 50%, which may be acceptable for low fluence tests. Other issues associated with the use of the various thermal neutron filters are summarized below.

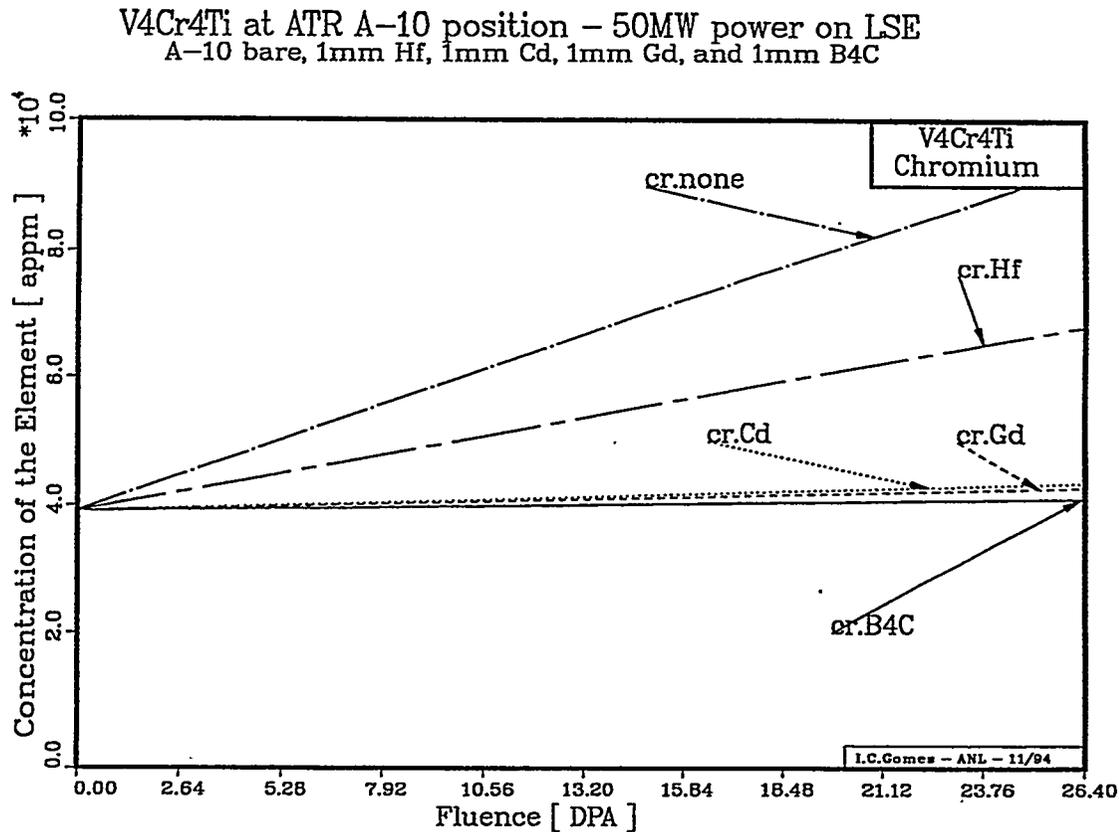


Figure 3. Influence of the different thermal neutron filters (1 mm thick) chromium in the A-10 hole of ATR.

- **Gadolinium:** The principal isotopes in the natural occurring gadolinium for thermal neutron absorption are the 155 and 157, which together account for 30.45% of the natural occurring gadolinium atoms. Burn-out of these isotopes will limit the lifetime of a gadolinium filter. In ATR with the lobe of the A-10 hole operating at 30 MW, a 1.7 mm layer of gadolinium is adequate for a fluence of 5 dpa. The increase in the chromium concentration under this scenario would be only ~ 0.007%. The additional gamma heating from the neutron absorption reaction was estimated to be 3 W/g in stainless steel.
- **B₄C:** Boron-10 is the isotope which absorbs the neutrons. In the ATR, under the conditions of this study, 1 mm of B₄C would last roughly 135 days or about 6 dpa in vanadium. But, the problem with B₄C is that for each neutron absorbed, one lithium-7 and one Helium-4 atoms are created. If the B₄C layer is confined, the pressure created by the helium gas would be unacceptable. On the other hand, if some space is left to allow the gas to flow to some kind of plenum, the lithium-7 production (about 20% of the boron atoms after 135 days of irradiation) would probably have a significant effect on the B₄C layer. Further studies are required to evaluate this solution.
- **Cadmium:** Cd-113 is the isotope which has a high absorption cross-section and its natural abundance is 12.22%. In the case studied, 1 mm-Cd cover would last about 50 days (~ 2 dpa) as an effective absorber.
- **Hafnium:** None of the hafnium isotopes have a very high cross-section in the thermal region. The highest cross-section for hafnium is in the epithermal region. The most important isotope in terms of reducing the neutron flux is Hf-177 and it has a natural abundance of 18.6%. A hafnium cover 1.1 mm thick would allow a fluence of 5 dpa with roughly a 0.5% increase in the chromium concentration.

CONCLUSION

To perform irradiation of vanadium in ATR is feasible and the transmutation from vanadium to chromium can be controlled using a thin filter cover of 1.7 mm of gadolinium or 1.1 of hafnium to reach fluences of 5 dpa with low transmutation rates.

REFERENCES

1. J.W. Rogers, R.A. Anderl, and M.H. Putnam, "Neutron Spectrum Studies in the ATR", Seventh ASTM-EURATOM Symposium on Reactor Dosimetry, Strasbourg, France, August 1990.
2. John Brasier, personal communication.