Panel Discussion

Prospects for Development of Low Activation Materials

Remarks of Nasr M. Ghoniem[1]

During the past 10–15 years, significant amounts of data have been accumulated on the radiation effects and mechanical properties of ferritic steels. The data indicates that these steels may have potential applications, with very significant improvements over austenitic steels, in fusion reactor designs. Ferritic alloys are normally strengthened by elements such as molybdenum and niobium, and are stabilized by nickel and copper. Additional impurities, which do not impact physical or mechanical properties, are introduced during the mining and or the manufacturing steps.

Our research indicated that if elements with long radioactive decay chains are eliminated in some way, we may have the potential of reducing the structure radioactivity. Although radioactive decay may not be totally eliminated, we can gain a substantial reduction factor in the level of radioactivity after shutdown. From this standpoint, we have concentrated our efforts on improving the mechanical properties of this class of alloys for design applications, and also on modifying the basic metallurgical structure in order to reach the goal of reduced activation.

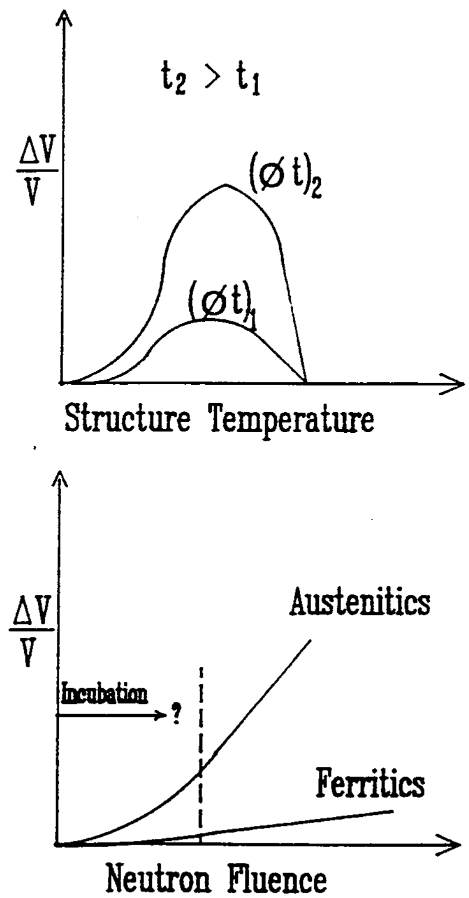

Fig. 1. Schematic representation of swelling vs. temperature and fluence for ferritic and austenitic steels.

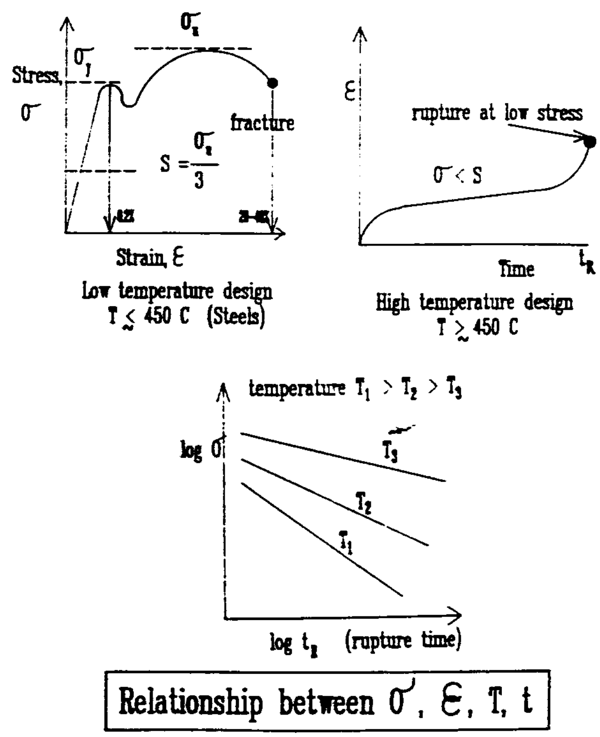

Fig. 2. Design criteria for high-temperature steels.

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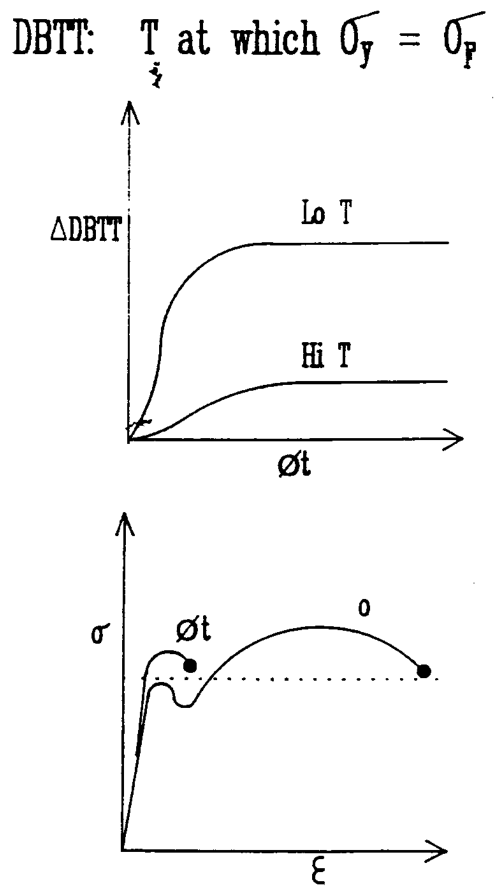

Fig. 3. Effects of neutron irradiation on the ductile-to-brittle-transition temperature (DBTT).

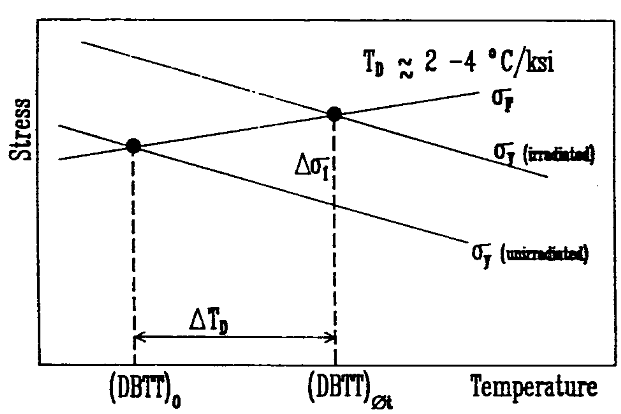

Fig. 4. Ludwig-Davidenkov diagram for the shift in the ductile-to-brittle-transition temperature (DBTT) by neutron irradiation.

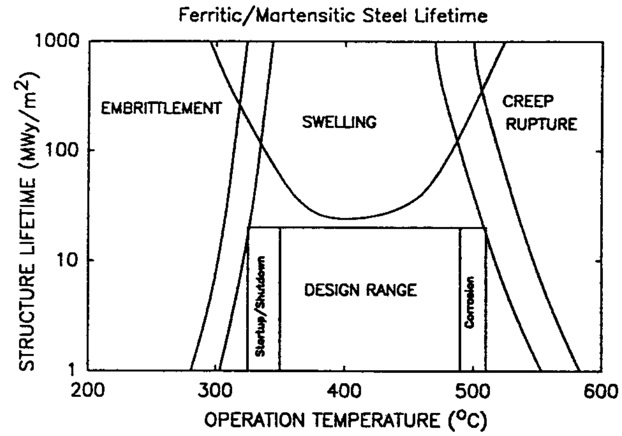

Fig. 5. Design window for martensitic/ferritic steels.

The accumulated data indicates that these ferritic alloys can offer several potential advantages over austenitic steels. Motivations for their use are: (1) low void swelling, (2) thermal stress resistance, (3) compatibility with liquid-metal coolants (Li and LiPb), (4) reduced harmful effects of helium generated by neutrons compared with effects on austenitic alloys, (5) low cost, and (6) easy fabrication and proven technology.

Swelling is a very significant design problem because of the size increase of the structure and the generation of expansion stresses. The data on ferritic alloys showed low neutron-induced void swelling. A comparison between the swelling behavior of ferritic and austenitic alloys is schematically shown in Fig. 1. Because the thermal conductivity is high and the thermal expansion coefficient is low, thermal stresses are low which enables ferritics to handle higher thermal loads. Compared to the austenitic class of alloys, ferritics are compatible with the liquid metals Li and $Li_{17}Pb_{83}$.

Neutrons also result in nuclear transformations which produce helium. This is a potent embrittling element because it reaches grain boundaries and leads to high-temperature embrittlement. Creep and high-temperature ductility are shown in Fig. 2. One of the most significant problems in ferritics is the low-temperature, neutron-induced embrittlement. Neutrons result in an increase in the transition temperature from ductile to brittle behavior. This limits the operation at lower temperatures, particularly during startup and shutdown of the fusion reactor. This is shown in Figs. 3 and 4.

From a design standpoint, a design window can be established on the basis of the available data. We have indicated only a possible scenario here. We should realize that conclusions are somewhat speculative because

1. RADIOACTIVE WASTE DISPOSAL
   - Mo, Nb, Ni, N, and Cu have been eliminated as alloying elements
   - ➡ Vacuum – Induction melting will qualify UCVS-1 to class C waste as defined by NRC-10CFR61

2. SAFETY
   - MPC for Mo and W are small, hence they were eliminated
   - ➡ BHP at shutdown is ≈ 100 times smaller than HT-9
   - ➡ V_2O_5 melts and does not vaporize

3. CARBIDE STABILITY FOR HIGH TEMPERATURE STRENGTH
   - Sequence of carbide formation (unirradiated):
     $M_3C \rightarrow M_3C + V_4C_3 \rightarrow M_7C_3 + V_4C_3 \rightarrow V_4C_3$
   - Cubic carbides (V_4C_3) are particularly good dispersion hardening components. V_4C_3 carbides do not grow rapidly at $T < 600°C$

4. DUCTILITY AT LOW TEMPERATURE
   - Vanadium – Manganese Steels (such as ASTM-A572 (1972)) have been used for applications in cold climates
   - Pre-irradiation DBTT can be very low for such steels

5. RESISTANCE TO TEMPER EMBRITTLEMENT
   - Caused by elements like P, Sn, Sb, Mn and Si
   - Watanabe factor, J, is a reasonable measure
   - $J = (Mn + Si)(P + Sn + Sb) \times 10^4$
   - ➡ For UCVS-1
   - ➡ $J \approx 42$ — no temper embrittlement

6. RESISTANCE TO VOID SWELLING
   - Pure Fe-Cr-C as well as commercial ferritic alloys have demonstrated resistance to void swelling
   - ➡ We expect UCVS-1 to demonstrate the same resistance

7. COMPATIBILITY WITH LITHIUM AND LITHIUM-LEAD COOLANTS
   - Fe_3C (cementite) and Mo_2C are vulnerable to lithium metal attack
   - High phosphorus contents enhance intergranular dissolution
   - High nickel contents enhance corrosion
   - ➡ Elimination of nickel reduced P, and the presence of V_4C_3 carbides may help with compatibility

Fig. 6. Motivations for the development of the low-activation ferritic steel UCVS-1.

our database is not, of course, for 14-MeV neutrons and we don't have the fluences required to reach design goals. The design window is shown in Fig. 5. The structural lifetime is measured in terms of the accumulated neutron energy flux (MW/m^2). This figure shows the range of neutron fluences and temperature regimes for fusion applications of ferritic alloys. On the high-temperature side, because ferritics have lower creep resistance than austenitics, they are limited to temperatures less than 500°C. However, since the swelling rate of ferritics is lower than that of austenitics, potential long lifetime (~40 MW/y) can be achieved. Depending on the particular reactor design, accumulated displacement damage fluences of 400–500 dpa (displacements per atom) can be realized with ferritic alloy structures. However, if we would like to meet the goal of low activation, considerable metallurgical modifications are needed.

In 1982, we started to develop an alloy, UCVS-1, at UCLA. This is about the same time the fusion materials program got interested in this class of alloys. Our motivations for the development of the UCVS-1 alloy are shown in Fig. 6.

Elimination of molybdenum, niobium, nitrogen, nickel, and copper, in addition to vacuum-induction melting to control the impurity levels of these elements, was one of the goals for developing UCVS-1. From a safety perspective, elimination of tungsten is also desirable. The development of UCVS-1 is just an example of what is possible in developing high-temperature ferritics. Subsequently, within the fusion program, many other ferritic alloys were developed which have shown even better mechanical characteristics.

The high-temperature strength of ferritics is usually maintained by additions of molybdenum and niobium. Without these elements, carbide stability at high temperature is a key problem which we have solved. In fact, we found out that some of the vanadium and tungsten

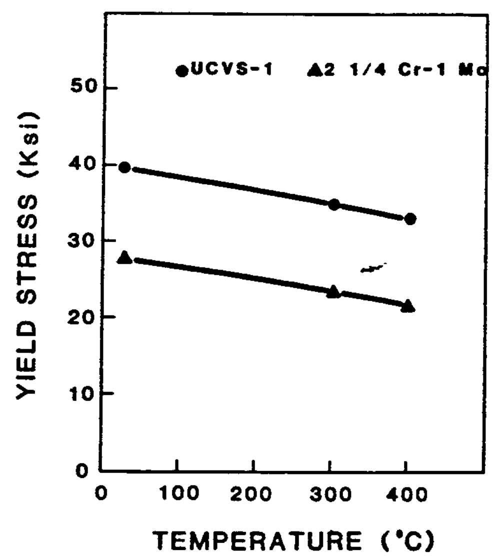

Fig. 7. Experimental yield stress dependence on temperature for UCVS-1 and 2-1/4-Cr - 1Mo.

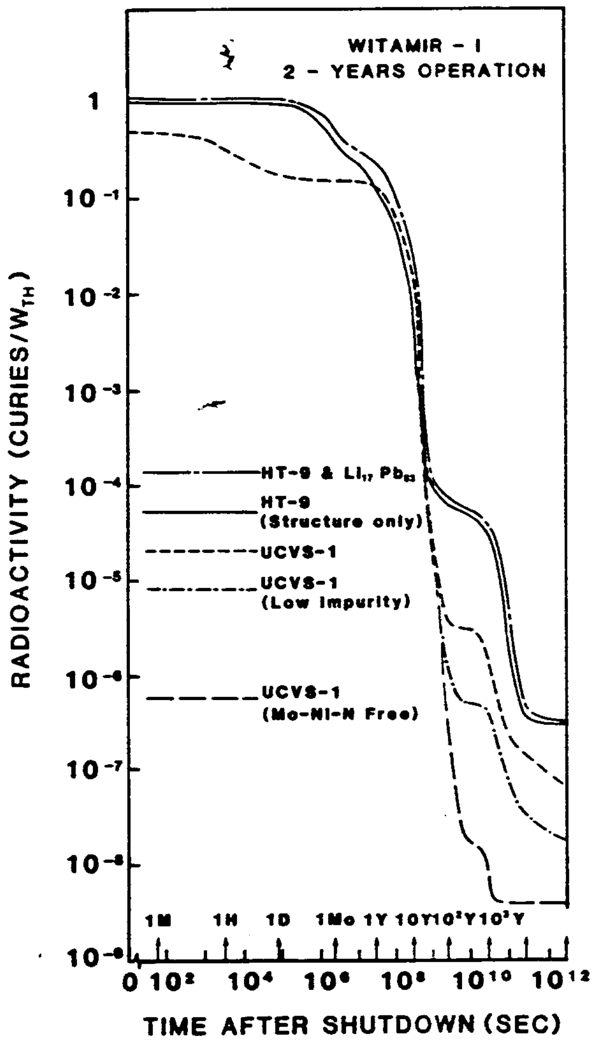

Fig. 8. Radioactivity vs. time for HT-9 and UCVS-1 alloys.

carbides, at least under thermal environments, are more stable than the corresponding molybdenum carbides. Carbide stability should reflect on the high-temperature strength. The yield strength for UCVS-1 in comparison to a commercial grade of almost the same composition (2-1/4-Cr - 1 Mo) is shown in Fig. 7. Following these principles, a number of alloys from the bainitic range, i.e., low chromium, to the martensitic range, i.e., high chromium, has been developed by various other groups. It is concluded that the high chromium range is much more advantageous than the low chromium range for fusion applications.

Radioactivity analyses for UCVS-1 and other commercial grades of ferritic alloys are shown in Fig. 8. Commercial impurity control of UCVS-1 shows a 25-fold reduction in the long-term radioactivity level (50–100 years) over HT-9. With a better control of the impurity levels (50 appm Mo, 100 appm Ni, and 100 appm N), two orders of magnitude reduction in the radioactivity can be obtained.

In conclusion, ferritic alloys have been developed for fusion applications. New alloys offer the advantages of good radiation damage resistance and, at the same time, show a significant reduction in the long-term radioactivity.

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