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13. ABSTRACT *(Maximum 200 words)*

Pinning centers have been studied in the high temperature superconductor (HTS) $YBa_2Cu_3O_{7-\delta}$, using damage centers created by neutrons, protons, high Z ions, and Uranium fission. The aim of this study was to increase the critical current, J_c, decrease the creep, and decrease the anisotropy while reducing cost and residual radioactivity. Such material could immediately be applied to make superior trapped field magnets, and may be applied to many other devices. Results are that $J_c = J_c(T, B_A)$ has been increased by factors of 10 to 42, depending on the operating values of temperature, T, and applied field. The resultant material also has the lowest cost, by a factor of 5-100, and has also the lowest radioactivity, by a factor of 5. The increases in J_c are maintained at high field (e.g., 14 Tesla). The effects on creep and T_c are small.

In other work a method was developed to, practically, eliminate creep by use of post activation cooling. In addition, the theory of cracking under magnetic pressure has been corrected, and experimentally confirmed.

14. SUBJECT TERMS
PINNING CENTERS, CREEP, HIGH FIELD PERMANENT MAGNETS, MAGNETIC PRESSURE CRACKING.

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MATERIALS DEVELOPMENT, AND CHARACTERIZATION FOR TRAPPED FIELD MAGNETS

FINAL PROGRESS REPORT

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PROF. R. WEINSTEIN

JANUARY 31, 1998

U.S. ARMY RESEARCH OFFICE

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UNIVERSITY OF HOUSTON

Final Progress Report

A. Statement of Problem

Our task deals with trapped field magnets (TFMs) made of high temperature superconductors (HTS), and the development of materials suitable for this. In order to increase the field of such magnets one must increase either the size or the critical current density, J_c, a measure of the current carrying capability. The magnitude of trapped magnetic field, B_t, which can be supported by high temperature superconductors (HTS) is given by $B_t \propto J_c f(d)$, where d is the diameter of the ingot of HTS. Our recent work has been devoted to increasing J_c, because the benefits are much broader than just application to trapped field magnets, and because the problems are more basic and challenging. Work to increase d continues as a background job.

The present proposal aims to improve J_c, and to improve or better understand the other HTS properties of creep, anisotropy, radioactivity, and cracking.

The goals of our work include:

i.) Increase J_c.

ii.) Study the effects of pinning center geometry on J_c, creep, and anisotropy.

iii.) Reduce residual radioactivity for irradiation methods which increase J_c.

iv.) Reduce creep.

v.) Increase grain diameter.

vi.) Study, and control, cracking and giant flux jump.

Major progress has been made in all of these areas except v.) due to limited time.

B. Summary of Most Important Results

1. Record Trapped Field

A trapped field of 10.1 Tesla has been achieved. This number can be put into perspective by noting it is a factor of 25 higher than SmCo, an excellent ferromagnet.[12,13] (See Fig. 1.)

The field achieved is a world record for a permanent magnet made of any material and operated at any temperature.

The 10.1 Tesla field was reached by utilizing basic TFM properties, discovered during this grant period, and reported below.

As a result of achieving 8.6 Tesla, our group was presented the Materials/Devices Award by the joint ISTEC(Japan)/MRS(USA) Program Committee of the 1995 International Workshop on HTS, Maui, Hawaii. As this award was presented the achievement of 10.1 Tesla was taking place.

2. Reduction of creep

Creep causes the decrease with time of the field of a TFM. The natural creep of $YBa_2Cu_3O_{7-\delta}$ (Y123) is about 5% per decade of time.

We cooled TFMs after they were fully activated (called post-activation cooling, PAC).[13] We learned that creep could be reduced by factors of 6.25, 197, and >1000 by PAC of ΔT= 2, 4, and 6K respectively. (See Fig. 2.) Thus in applications with temperature control, creep can be made to be, practically, zero.

3. Pinning Center Geometry

Pinning centers are faults in a superconductor. These reduce or prevent movement of flux lines, an energy dissipating mechanism, and consequently increase J_c. The improvement in

J_c is known to depend on the detailed geometry of the pinning center. Using radiation as a tool, one can control the pinning center geometry.

We have studied "point defects" introduced by high energy protons (p^+) and neutrons (n°); "columnar defects" caused by charged high energy ions (Xe, Kr, Ne); and defects obtained by introducing Uranium into the HTS precursors, processing the HTS, and then irradiating with thermal neutrons to cause fission. This latter process is called the U/n method.

p^+ bombardment increase the trapped field, B_t, in textured material by a factor of 3.5. J_c at constant field is increased by ~10 as a result of the point defects introduced.

Columnar defects, introduced by high Z ions increase J_c by factors of, typically, 3.5. The increase is limited by the extensive damage done to the HTS. e.g., to trap 10.1 Tesla the irradiation must be high enough to entirely destroy the superconductor.

The U/n method produces the best of all results[1-3] and is described below.

<u>4. J_c</u>

The increase of J_c in the U/n method is very large. First, there is an increase of 65% in trapped field (82% in J_c) obtained from the chemical results of adding U. (See Fig. 3.) We have studied the U deposits and found them to be $(U_{0.6}Pt_{0.4})YBaO_3$. These deposits average 300nm in size, and themselves act as pinning centers. (See Fig. 4.)

We further found that neither critical temperature, T_c, nor creep as measured by % field lost per decade of time, are worsened by the presence of U. (See Fig. 5.)

Subsequent neutron irradiation causes fission of U235. This fission fragment damage (See Fig. 6) further increases J_c dramatically. Fig. 7 shows the increase in trapped field, and Fig. 8 shows the increase in J_c. Overall, increases in J_c vary from factors of 10 to 42, depending upon temperature (T) and applied field (μH_A).

The resulting magnitudes of J_c are impressive. J_c(77K, 0 Tesla) is 300,000A/cm^2, a level never before seen in textured HTS. 1,000,000A/cm^2 is achieved at 50K, 0T. In addition, the improvement holds up to very high field. Thus, at 50K the enhancement of J_c at 14 Tesla is over a factor of 10. (See Fig. 8.)

As a result of these record setting values of J_c we were presented the Strong Pinning Center Award by the ISTEC/MRS Program Committee of the 1997 International Workshop on HTS, Big Island, Hawaii. This is the second award we received from that group.

We found that T_c and creep were worsened by irradiation. However at the best fluence (~4 x 10^{16}n/cm^2) the changes are slight. (See Fig. 9.)

A further finding of our work was that the anisotropy of HTS is reduced ~30% by the best pinning center geometries.

One U/n tile traps 2.1 Tesla and a group of 4 U/n tiles traps 3.1 Tesla at 77K. These are record fields at 77K.

5. Cracking

The interaction of J_c and B_t, in a trapped field magnet results in an outward pressure. The ultimate field which can be trapped in a TFM is the field at which this magnetic pressure cracks the TFM. We studied this process as a problem which had to be understood prior to producing 10.1 Tesla TFMs.[13,14] We found that the cracking strength of Y123 would support a trapped field of 12 Tesla. We completed our study by cracking several samples, using magnetic pressure.[14] There is a paper in the literature by Collings, Proc. 4th World Congress on Superconductivity, Orlando (1994) reporting the detailed cracking theory. We found these results to be in error in that the author had assumed activation had been completed prior to cracking. We find that cracking always occurs *during* activation. We generalized the theory to include activation, made specific theoretical predictions, experimentally cracked TFMs, and found excellent agreement between the new theory, and experiment.

6. The U/n Method: Cost and Radioactivity

The U/n pinning centers are so successful in increasing J_c that we evaluated the practicality of using U/n TFMs in several applications. e.g., TFMs, power lines, particle separators and spacecraft docking.

Two variables enter into practical applications which do not enter into the basic study: cost and residual radioactivity.

(a) Cost: The competitive methods of p^+ induced defects, n° induced defects, high energy ions, and p^+ induced fission result in the following costs, for a standard TFM, 2cm diam., 0.8cm thick.

High energy ions:	$100,000/sample
p^+ induced fission:	$ 3,500/sample
p^+ defects:	$ 1,750/sample
n° induced defects:	$ 150/sample

The cost of a sample of the standard size processed by the U/n method is $30. Thus the U/n method not only gives the best results for J_c, but it does so at the lowest cost.[1,2]

(b) Residual Radioactivity: the U/n method also results in the lowest radioactivity.[1,2] The resultant radioactivity is five times lower than each of the above "competing" methods.

The absolute magnitude of the gamma radioactivity is 200 nanocuries/gm at 6 mo. after irradiation. This is to be compared to 1μc of α activity in smoke alarms, and typical freedom from safety requirements for shipping 10-100μc of various isotopes.

We are still engaged in lowering the residual radioactivity of the U/n method, and believe we can reduce it to 50nc/gm.

7. Summary

A 10.1 Tesla TFM has been produced (and an award given to us).

A method has been discovered to reduce creep, practically, to zero.

The effect of pinning center geometry has been studied using radiation probes of p^+, n°, Xe, Kr, Ne, and the U/n method.

The U/n method is best, and has set a world record J_c for textured materials. (An award was given to us for this achievement.)

The U/n method not only produces the world's best textured material, but it does so at the lowest cost/sample and the lowest radioactivity/sample of any of the less effective competitive processes.

Cracking has been studied experimentally and theoretically. The theory of cracking has been rewritten by us, and now theory and experiment agree that TFMs will crack if B_t>12 Tesla. This limit can be increased if the HTS can be strengthened.

The U/n method is now being pursued in the HTS systems Nd123, Sm123, BiSCCO, mercury system, and thick films. This work involves a collaboration of leading labs in Australia (Univ of Wollongong), Austria (Atominstitut, Vienna), Germany (Dresden), Japan (ISTEC), and our lab in the USA.

C. Personnel, and Publications

1. Scientific Personnel Supported:

R. Weinstein, Prof.
Y. Ren, Sr. Post Doc
J. Liu, Jr. Post Doc
D. Parks, Engineer

W. Hennig, Grad Student
A. Gandini, Grad Student
T. Nemoto, Grad Student
R. Sawh, Lab Manager
6 undergraduate lab assistants

2. Publications

1. R. Weinstein, R. Sawh, Y. Ren, M. Eisterer and H. Weber, Invited Paper, "The Role of Uranium Chemistry and Uranium Fission in Obtaining Ultra High Jc in Textured Y123." Symposium of Processing and Critical Current of HTS, Wagga Wagga NSW, Australia, 2-4 February 1998, also Superconductor Science and Technology (Special Issue, in compilation)

2. R. Weinstein, Invited Paper, "The Role of Uranium, With and Without Radiation in the Achievement of $J_c \sim 10^5 A/cm^2$ in Large Grain HTS," Proc. of the 1997 Workshop on Processing of Superconducting (RE)BCO Large Grain Materials, Cambridge, UK, July (1997), Journal of Materials Science and Engineering B, (in press).

3. R. Weinstein, Invited Paper, "Large Increases of J_c in Textured Bulk HTS Based upon Chemical and Radiation Effects of Uranium," Proc. of the 3rd Joint ISTEC/MRS International Workshop on Superconductivity, Hawaii, June (1997), in compilation.

4. Y. Ren, R. Weinstein and R. Sawh, Selected Talk, "New Chemical Pinning Center from Uranium Compound in Melt Textured YBCO," Proc. of 5th International Conf. on Materials and Mechanisms of HTS, Beijing, Feb (1997), Physica C, 282-287 (1997) 2275.

5. Y. Ren, R. Weinstein, R. Sawh, and J. Liu, Selected Talk, "Isotropic Short Columnar Pinning Centers from Fission Fragment Damage in Bulk Melt-Textured YBCO," Proc. of 5th International Conf. on Materials and Mechanisms of HTS, Beijing, Feb (1997), Physica C, 282-287 (1997) 2301.

6. R. Sawh, R. Weinstein, Y. Ren, Poster Presentation, "Chemical Pinning Centers Including Uranium," Materials Research Society Fall Meeting, Boston (1996)

7. R. Weinstein, R. Sawh, Y. Ren, Selected Talk, "Fission Fragment Pinning Centers," Materials Research Society Fall Meeting, Boston (1996)

8. R. Weinstein, R. Sawh, Y. Ren, and J. Liu, "Isotropic Short Columnar Pinning Centers," Proc. 9th Internat. Sympos. on Supercon., Sapporo (Oct 1996), Eds. S. Nakajima and M. Murakami, Springer-Verlag, p. 539 (1997)

9. R. Weinstein, R. Sawh and Y. Ren, "New Chemical Pinning Center," Proc. 9th Internat. Sympos. on Supercon., Sapporo (Oct 1996), Eds. S. Nakajima and M. Murakami, Springer-Verlag, p. 543 (1997).

10. I.G. Chen, J. Liu, R. Weinstein, and Ravi Sawh, "Effect of Internal Uranium Fission on the Critical Current Density of YBaCuO Melt-Textured Superconductors," Proc. 9th Internat. Sympos. on Supercon., Sapporo (Oct 1996), Eds. S. Nakajima and M. Murakami, Springer-Verlag, p. 657 (1997)

11. Roy Weinstein, Invited Paper, "Permanent Magnets of High Temperature Superconductor," Proc. of International Workshop on High Magnetic Fields, Materials and Technology, Tallahassee (Feb 1996) Editor H.J. Schneider-Müntaü, World Scientific Press, 1997.

12. Roy Weinstein, Invited Paper, "Very High Trapped Fields: Cracking, Creep, and Pinning Centers," Proc. of 10th Anniversary HTS Workshop on Physics, Materials and Applications, Houston, edited by W.K. Chu, D. Gubsner, and K.A. Müller, World Scientific Press, p. 625 (1996)

13. J. Liu, R. Weinstein, Y. Ren, R.P. Sawh, C. Foster, V. Obot, "Very High Field Quasi Permanent HTS Magnet with Low Creep," Proc. of the 1995 International Workshop on Superconductivity, pg. 353, Maui (June 1995)

14. Y. Ren, R. Weinstein, J. Liu, and R. Sawh, "Damage Caused by Magnetic Pressure at High Trapped Field in Quasi-Permanent Magnets Composed of Melt-Textured YBaCuO Superconductor," Physica C, 251, 15 (1995)

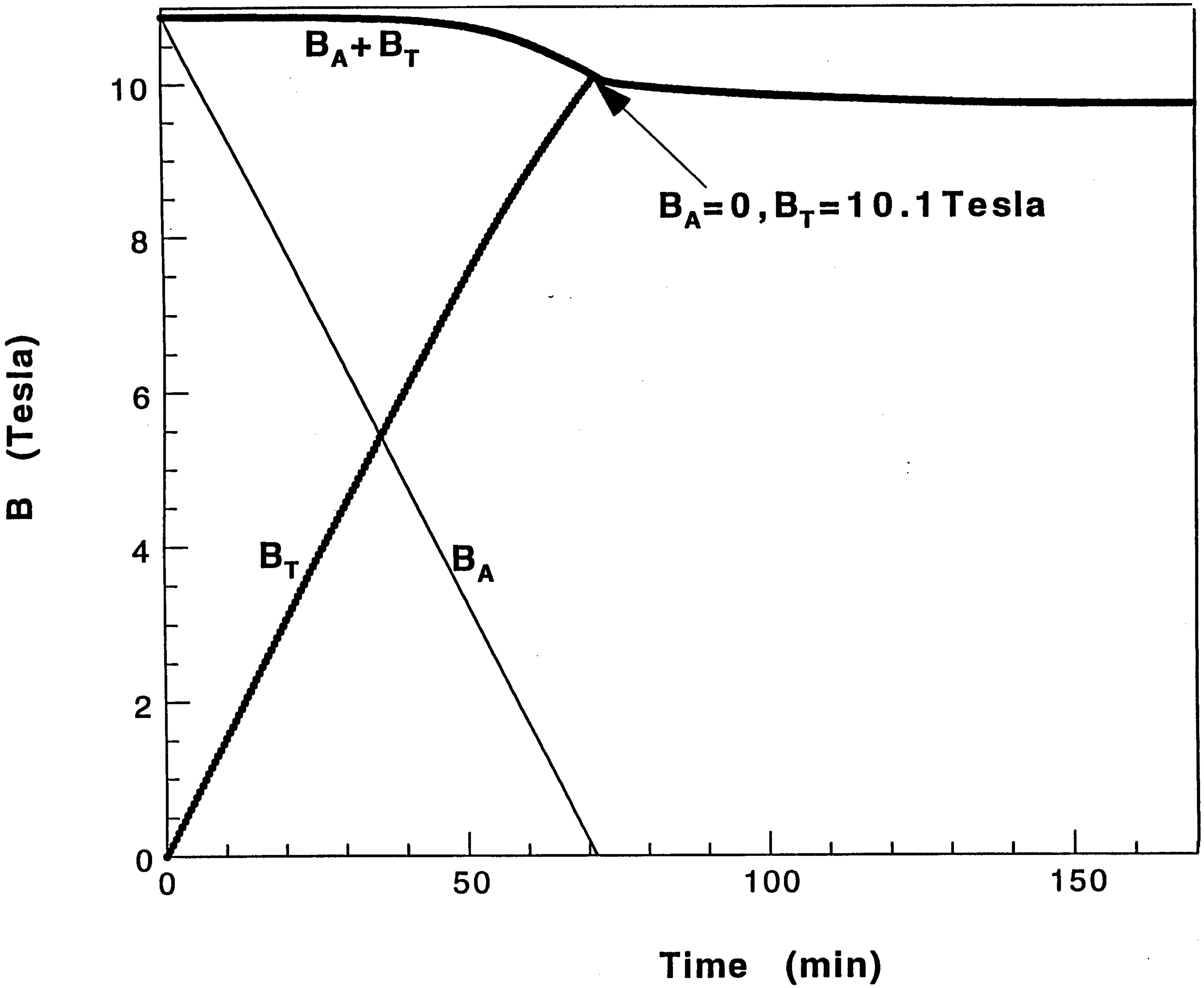

Fig. 1. Activation of Y123 TFM to 10.1 Tesla. Size of TFM=2cm diam. x 3.3cm long. As applied field, B_A, is lowered, trapped field, B_t, increases

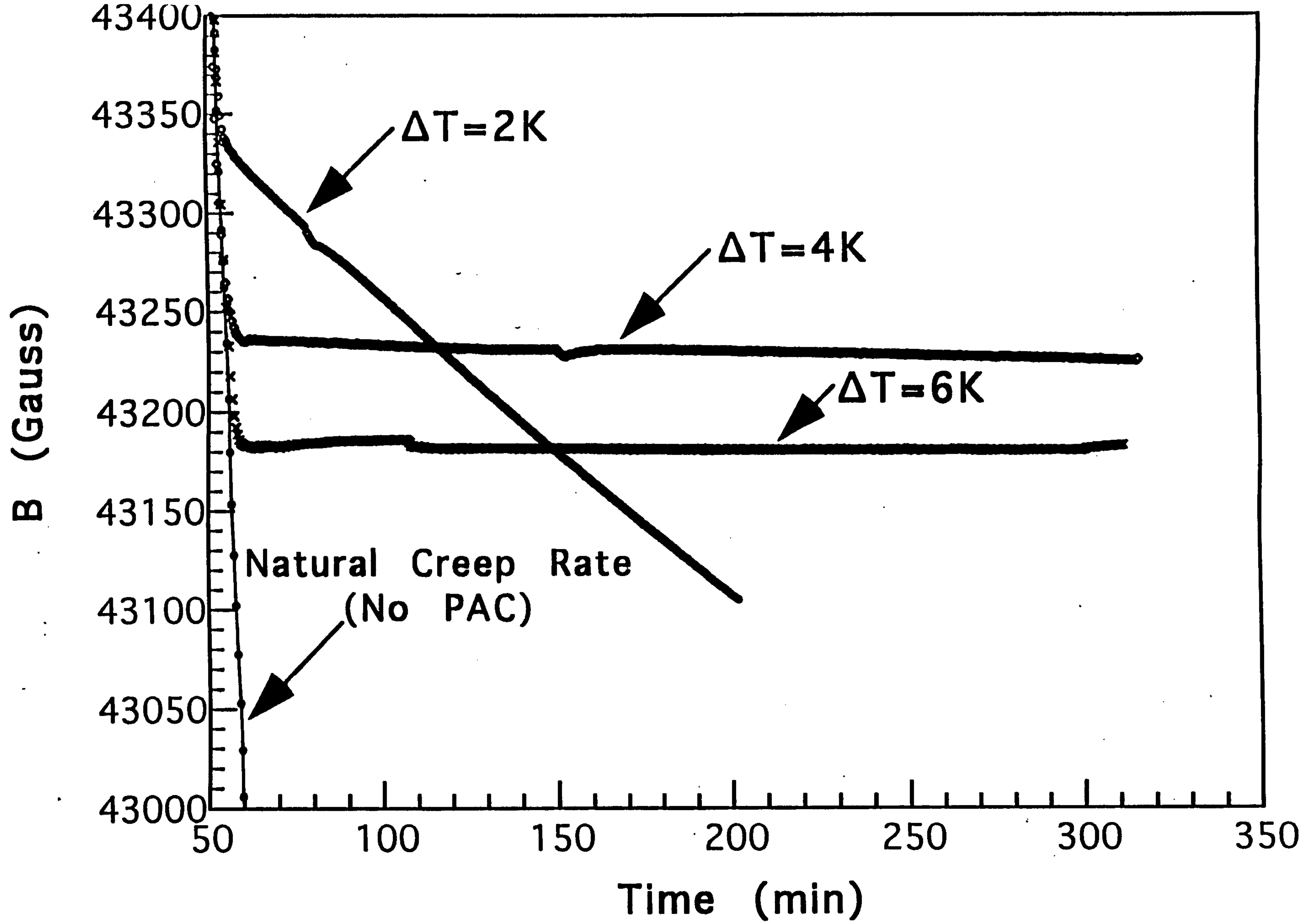

Fig. 2. Post Activation Cooling. Natural creep is given by the nearly vertical line on left. Other lines show reduced creep for ΔT=2, 4, 6K post activation cooling.

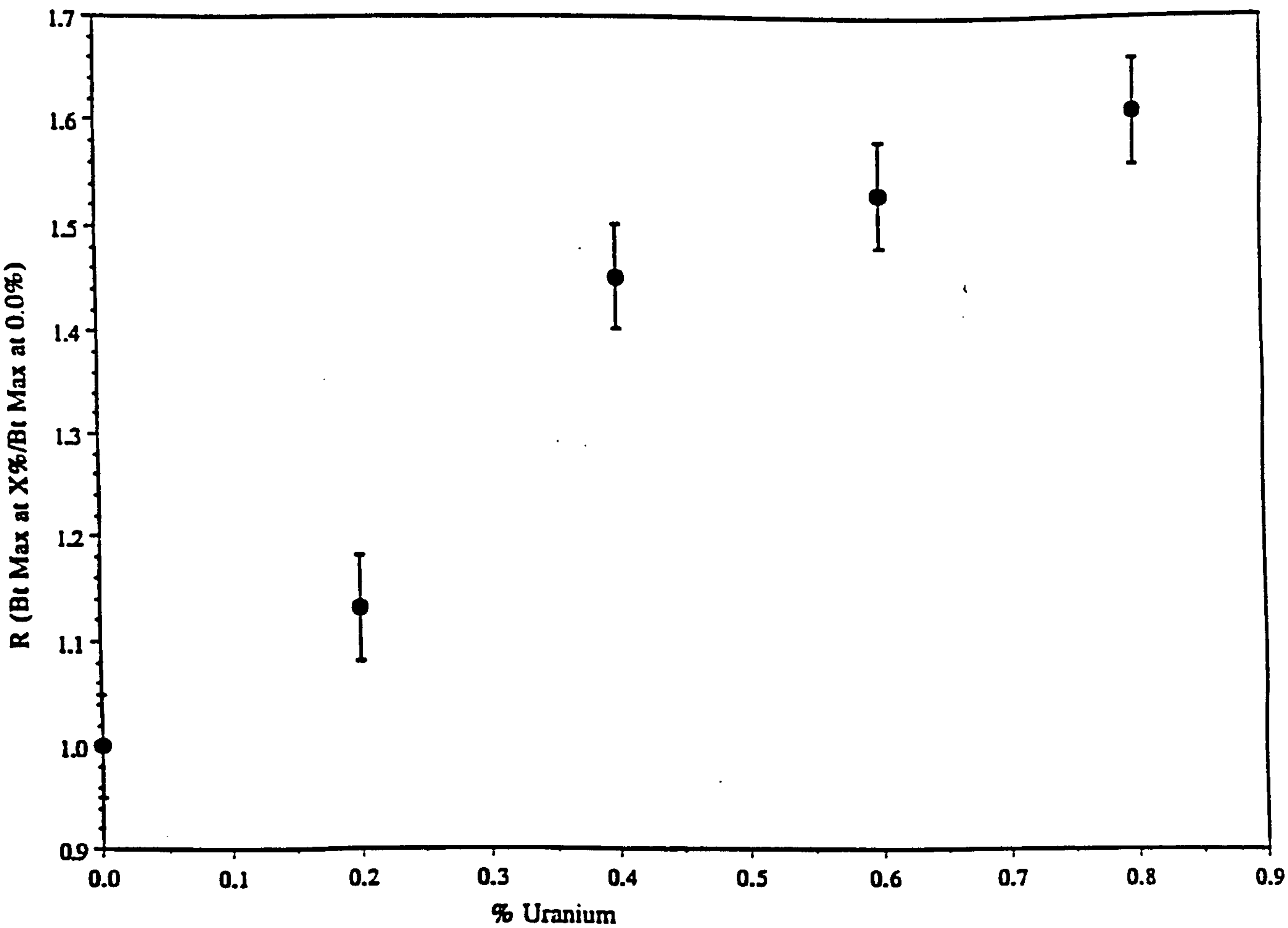

Fig. 3. R vs. %U(wt), showing effects of U deposits prior to irradiation. R=trapped field with U/trapped field with 0%U.

Fig. 4. TEM photomicrograph of a deposit of $(U_{0.6}Pt_{0.4})YBa_2O_6$, in the matrix of Y123.

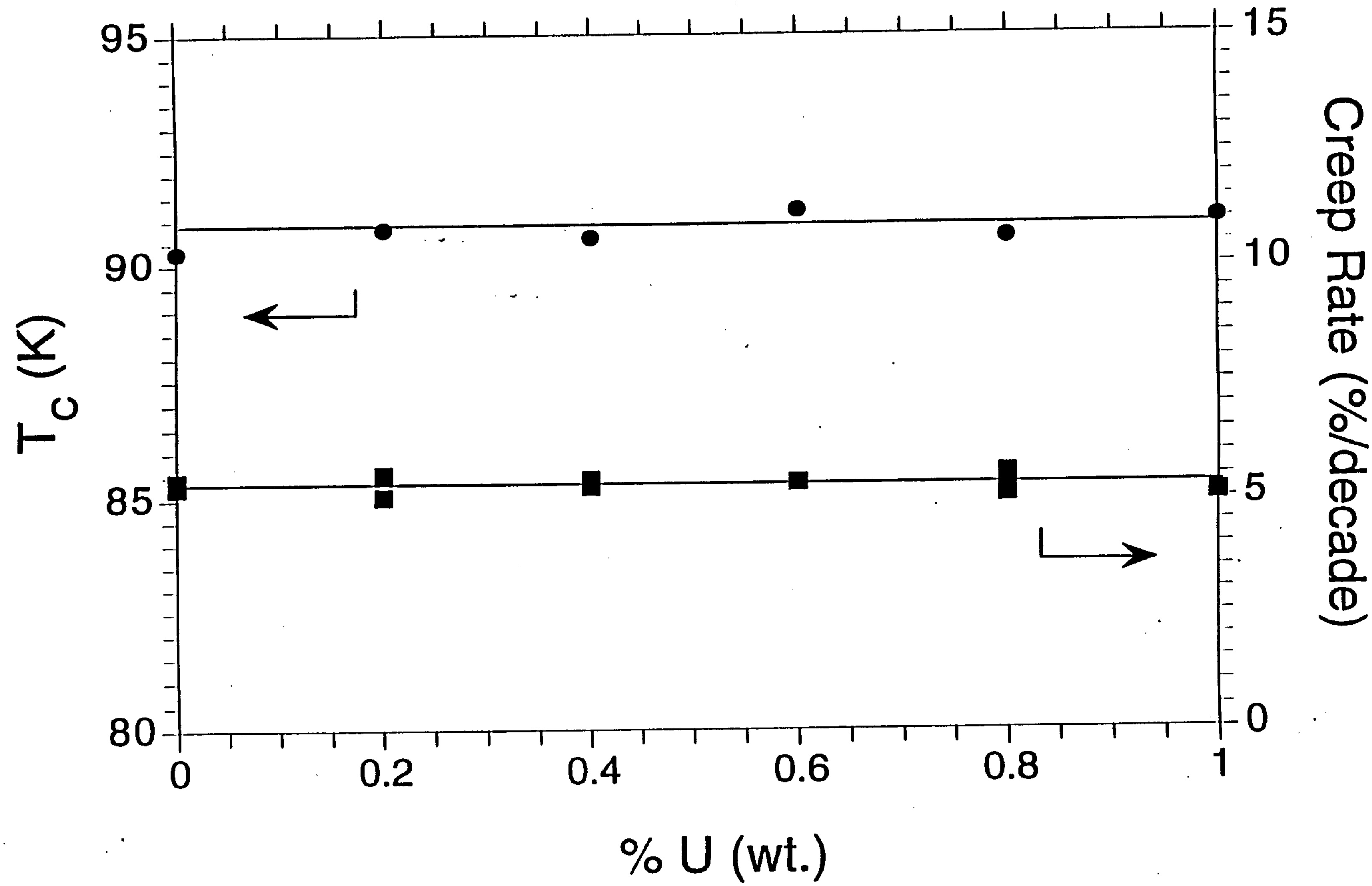

Fig. 5 (a.) T_c vs. %U in U-Chem method. (b.) Creep parameter β vs. %U in U-Chem method, where $B_{trap}(t_2) = B_{trap}(t_1) \times (1-\beta \log t_2/t_1)$.

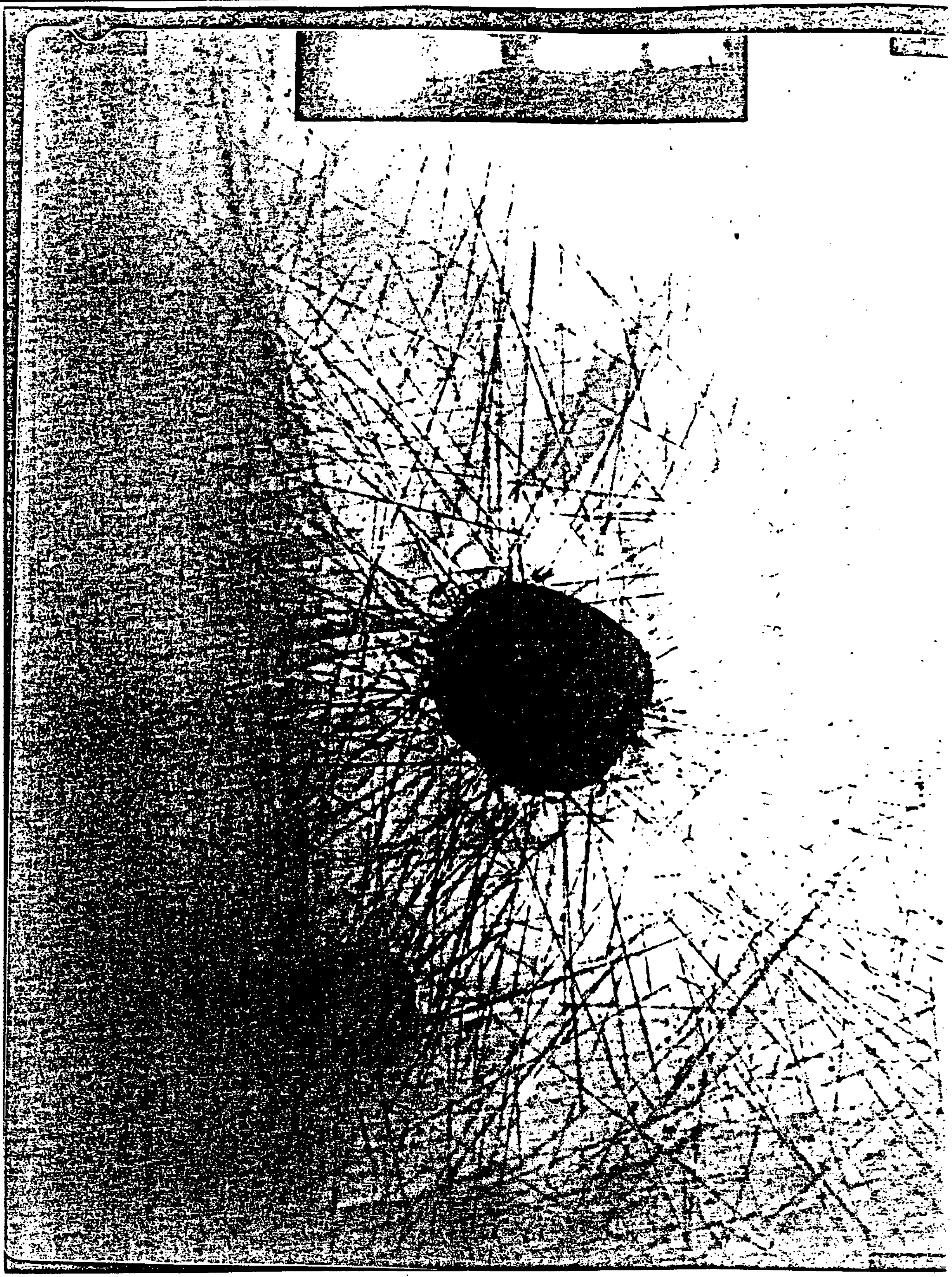

Fig. 6. TEM photomicrograph of a deposit of $(U_{0.6}Pt_{0.4})YBa_2O_6$, of diameter 300nm. Criss-cross lines are damage columns from fission fragments of U235.

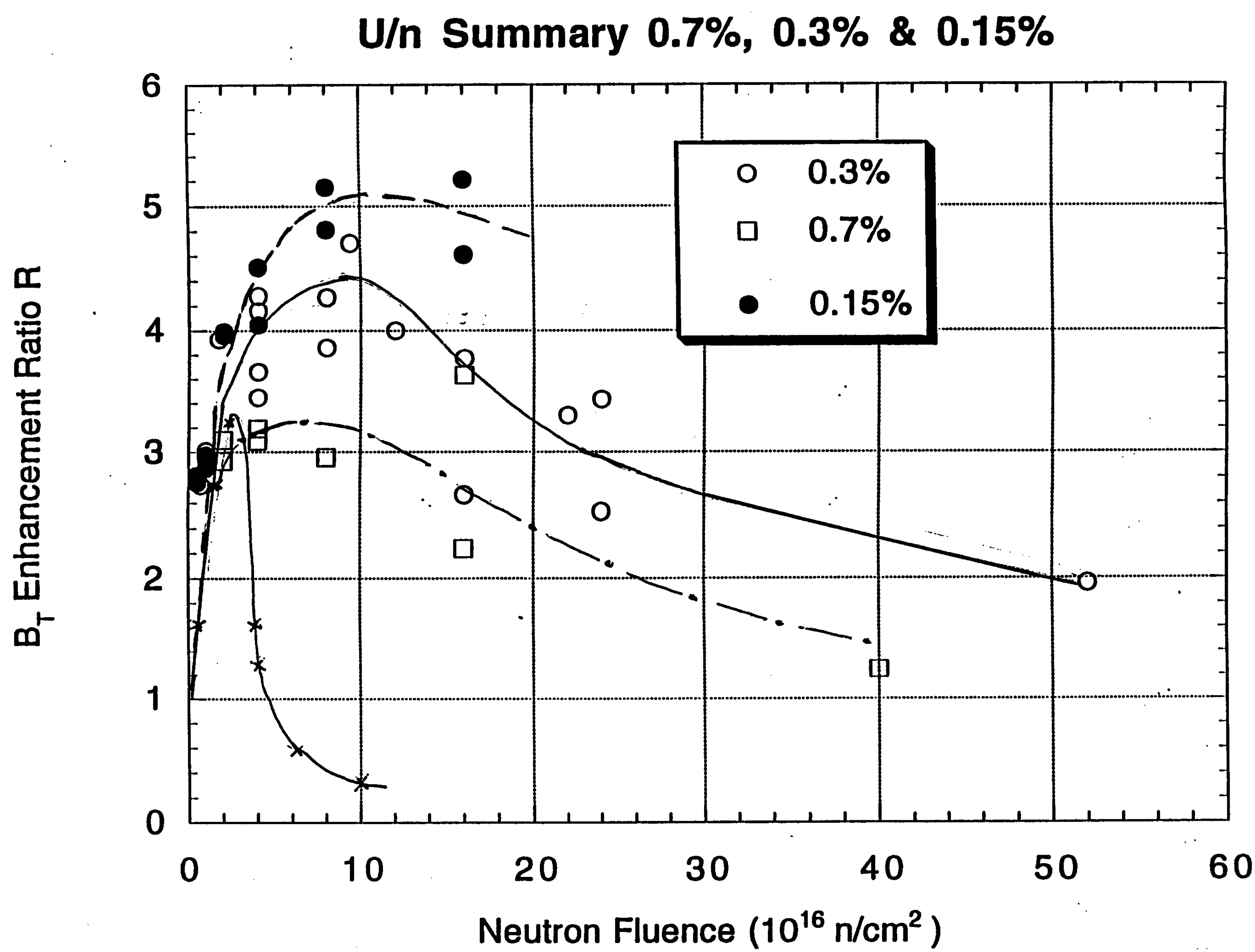

Fig. 7. Increase in trapped field vs. neutron fluence for 0.7, 0.3 and 0.15%U(wt). Further data at 0.075%(wt), not shown, indicates peak is near 0.15% wt.

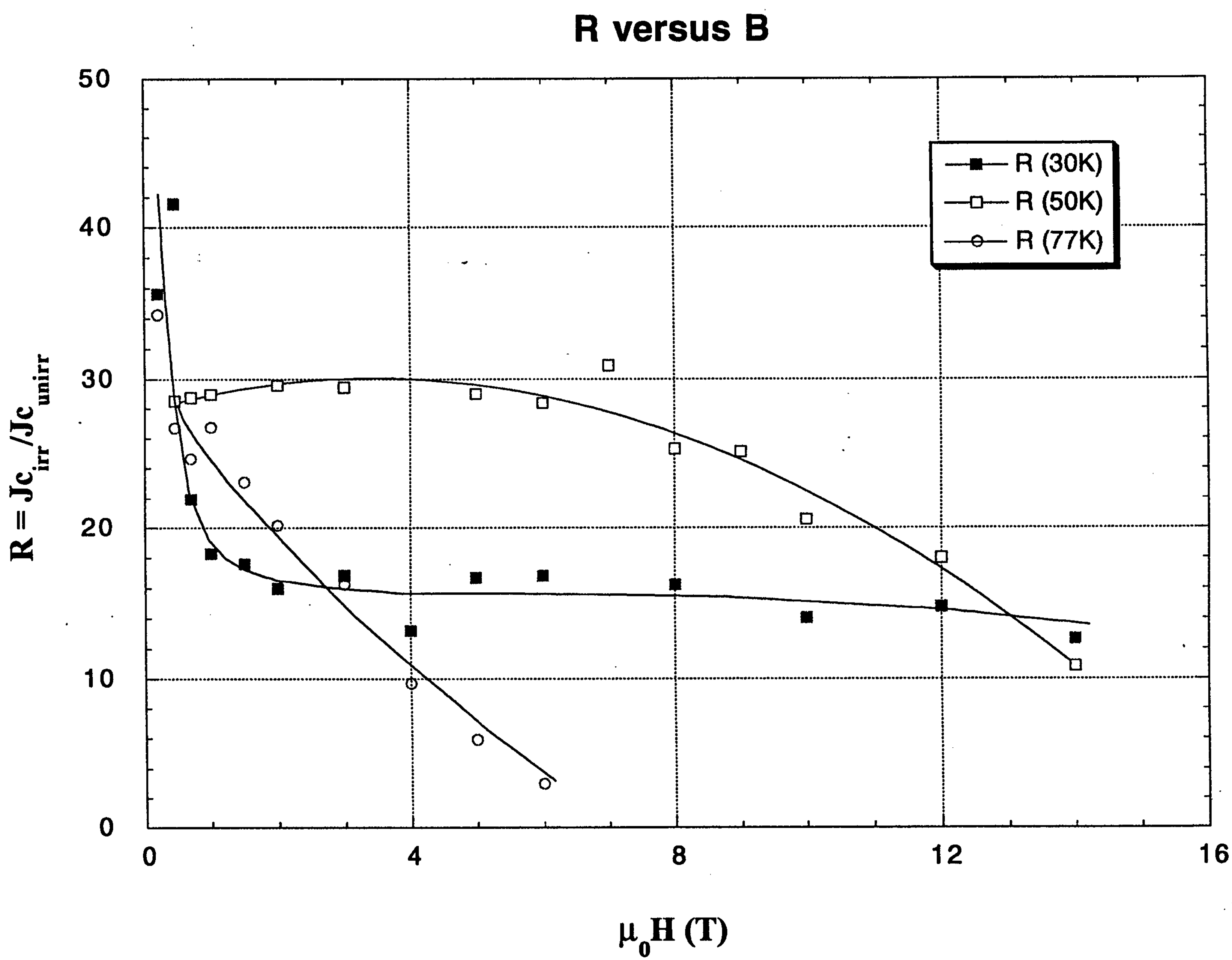

Fig. 8. Increase in J_c by U/n method, as a function of applied field, μH_A, and temperature.

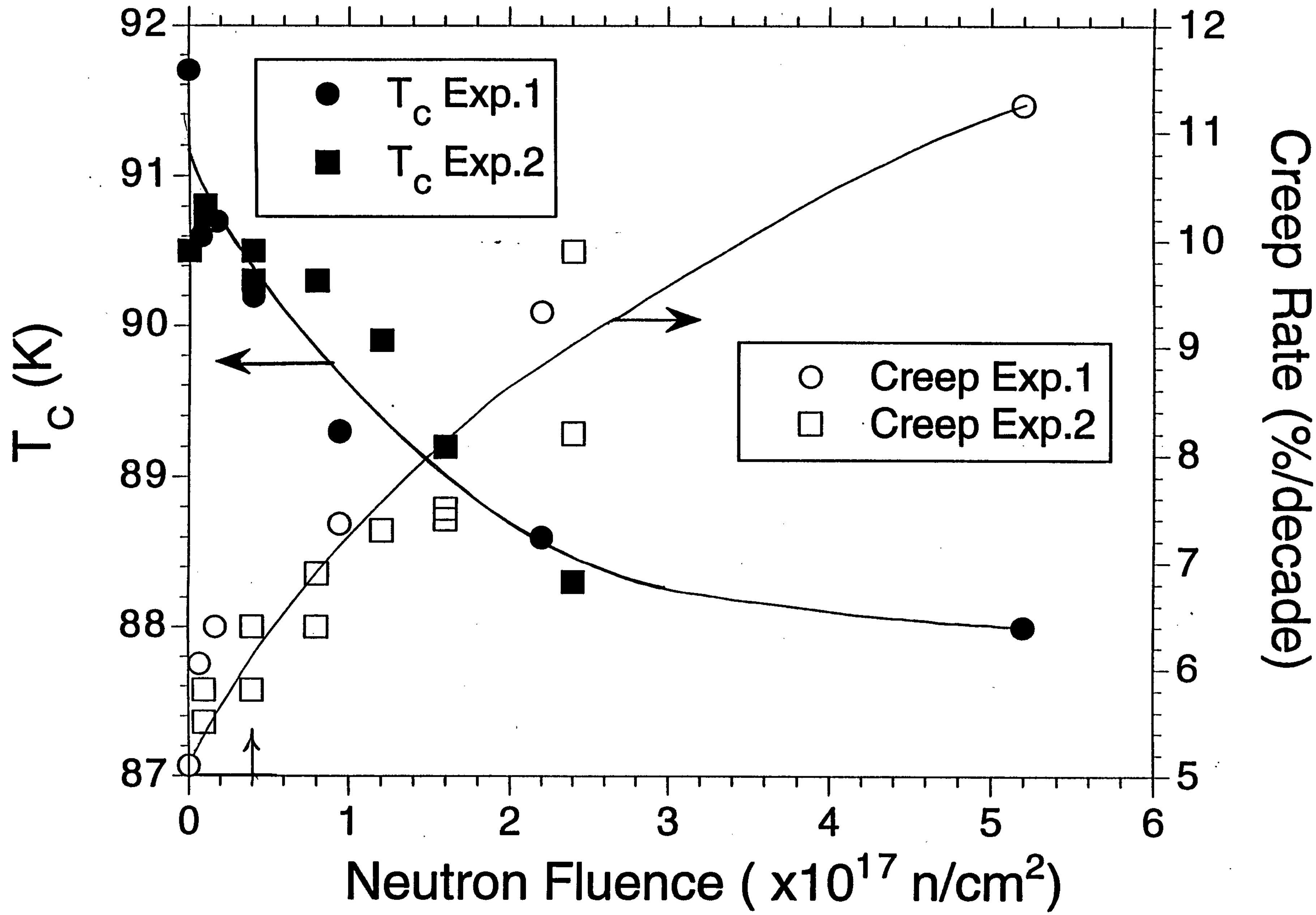

Fig. 9. (a) Variation of T_c with neutron fluence, F_n, in units of 10^{17}n/cm^2.
(b) Variation of creep %/decade of time vs. F_n. Note expected operating point is 0.4 x 10^{17}n/cm^2, where changes to T_c and creep are small.