LOCA Research Information Letter
RIL-0801 (May 30, 2008)

Public Meeting
September 24, 2008

Ralph Meyer
Division of Systems Analysis
Office of Nuclear Regulatory Research

Mandate for This Work

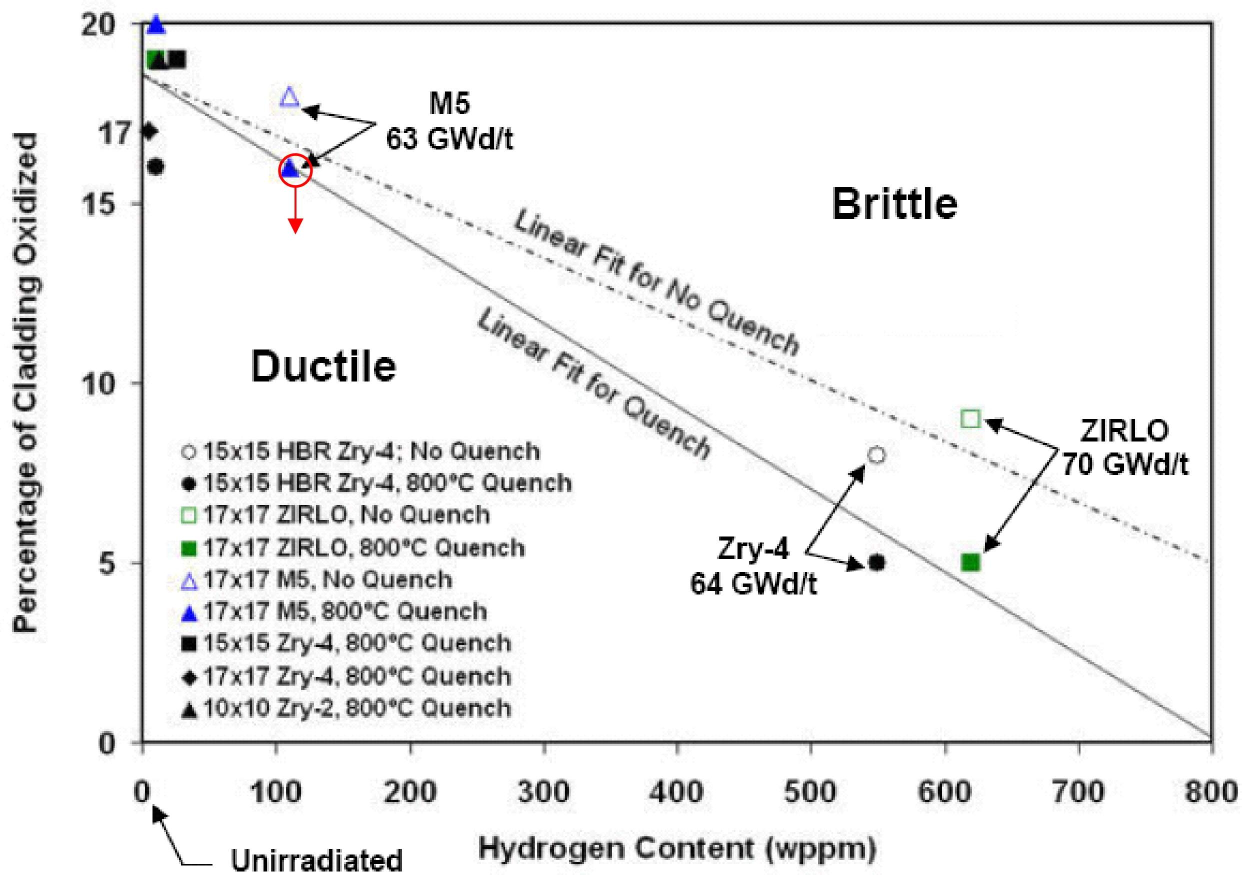
On March 31, 2003, the Commission approved the staff's recommendation to modify the criteria in 10 CFR 50.46 to provide for a more performance-based approach that would enable licensees to use cladding materials other than Zircaloy and ZIRLO without an exemption.

SRM on SECY-02-0057

Research Support for RIL-0801

- Argonne National Laboratory – funded by NRC with industry cooperation, NUREG/CR-6967
- Kurchatov Institute – funded jointly by NRC and IRSN (France) with additional funding from TVEL (Russia), NUREG/IA-0211
- Halden Reactor Project – bilateral project funded by NRC, IFE/KR/E-2008-004

Summary of Embrittlement Data



Applicability of Embrittlement Data (1 of 2)

- Cladding temperatures would have to remain no higher than 1204ºC (2200ºF) because embrittlement occurs at lower oxidation values for higher temperatures.
- Calculations of cladding oxidation use the Cathcart-Pawel equation for weight gain of fresh Zircaloy because all of the data in Figure 1 (of the RIL) were correlated with that parameter.
- Manufacturers or licensees would have to provide hydrogen-versus-burnup correlations because hydrogen absorption might vary for different materials and operating conditions.
- Some periodic testing would be needed to ensure that manufacturing processes had not changed in a way that would degrade the performance of the cladding material under LOCA conditions. Such testing could be done on as-fabricated material and would be relatively easy to conduct. Appropriate testing procedures could be defined.

Applicability of Embrittlement Data (2 of 2)

- The Cathcart-Pawel equation for two-sided oxidation is used for high-burnup fuel to account for oxygen diffusion from the inside diameter of the cladding, although there would be no heat associated with a metal-water reaction on the inside diameter.
- Breakaway oxidation would have to be avoided by using an additional time limit based on tests for each cladding material. These tests could be done on as-fabricated material and would be relatively easy to perform. Appropriate testing procedures could be defined.
- The embrittlement thresholds described above would apply only to fuel rods made with zirconium-alloy cladding and containing oxide fuel pellets.

Adequacy of Embrittlement Data

The present set of data is substantially larger and more precise than the data set on which the original rule was based, and the staff of the Office of Nuclear Regulatory Research recommends that the data summarized in this RIL be considered as the basis for rulemaking to revise 10 CFR 50.46(b).

Industry Cooperation

- Formal industry cooperation in ANL project since 1998
- EPRI has provided the high-burnup fuel rods used in this project
- Areva, GNF, and Westinghouse have provided unirradiated cladding for testing in this project
- Detailed (2-day) program review meetings have been held each year with industry representatives
- Non-industry representatives from international organizations have also participated in the program review meetings

Major Industry Comments

- Basis for criteria (strength or ductility) questioned in 9/9/03 EPRI letter and 10/24/03 public meeting. Resolved in 2/25/04 NRC letter to EPRI.
- "F-factor" and corrosion approach criticized by industry at 2/2/07 ACRS meeting. Approach dropped and replaced with hydrogen concentration.
- Validity of ID oxygen pickup away from balloon questioned by industry at 2/2/07 ACRS meeting. NRC funded special Halden investigation to confirm this phenomenon.
- Absence of testing with irradiated M5 and ZIRLO cladding criticized by industry at 2/2/07 ACRS meeting. NRC delayed project to complete those tests.
- Westinghouse letters 9/24/07 and 6/12/08 describe discrepancies in breakaway oxidation testing. Issue being actively addressed by ANL and Westinghouse and will not impact rulemaking.
- Other comments have been made in response to the 7/31/08 Federal Register notice, and we are prepared to discuss them today.

Other LOCA Phenomena

Several other fuel-related LOCA phenomena are under investigation or consideration in the NRC's research programs, but they are not needed to revise this part of the rule and they are not the subject of this RIL.

- Axial Fuel Relocation
- Loss of Fuel Particles through a Rupture Opening
- Ballooning and Flow Blockage

BACKUP NOTES

Ralph O. Meyer

September 25, 2008

Response

Strength versus Ductility

Thirty five years ago, proposals to base LOCA requirements on strength were discussed at the big ECCS hearing. The Commission decided against strength-based criteria because they did not believe that loads during a LOCA could be known and therefore they were unable to determine what minimum strength to require. Instead, they adopted ductility-based criteria.

When NRC started the current research project about ten years ago, the goal was to determine the effects of fuel burnup on the existing LOCA criteria. That has been done. About midway through this research, the discussion of strength-versus-ductility came up again. At that time, NRC noted that the basis for the criteria should not be changed, and we pointed out that load assessment was not included in our research plans.

Of course it would be possible to change the basis for the LOCA criteria. But it would be necessary to define LOCA loads as well as to characterize fuel rod strength. If the U.S. industry wants to go in this direction, a petition can always be made to NRC under 10 CFR 2.802. However, this would be far more difficult than measuring the effect of burnup on ductility, and it would involve a reduction in safety margin that might be controversial.

September 22, 2008

Response

2-Sided Oxygen

[Concerns about a requirement for 2-sided oxygen uptake are greatly exaggerated.]

One comment said that the observed alpha layer was only ~25 microns in thickness suggesting that it was not significant. The comment also suggested that the oxygen uptake from the outer surface and the ID might not be the same. In fact the equal alpha layers shown in the RIL prove that the amount of oxygen entering from the ID and OD are identical, regardless of the magnitude of layer thickness. Based on in-reactor tests, hot-cell tests, controlled laboratory tests, and theoretical considerations, there is no question that equal ID and OD oxygen uptake can occur at high burnup. The only remaining question is about the progression of this effect with burnup because it does not occur in fresh fuel.

The related concern is that a requirement for 2-sided oxygen pickup in a LOCA analysis might lead to unnecessary conservatism. This is unlikely. Every fuel rod that reaches oxidizing temperatures during a LOCA has experienced rupture such that 2-sided oxygen pickup is already required. In one case where enough information exists to do a comparative calculation, 2-sided oxygen pickup in the non-ruptured PCT node was somewhat less than 2-sided oxygen pickup in the ruptured node such that including this requirement would have had no effect.

Although one calculation does not prove the general case, it is straightforward to include 2-sided oxygen pickup (no ID metal-water heat in the non-ruptured node) in the ECCS analysis. This will insure that high-burnup fuel is protected in the unlikely case that analysis in the balloon is not limiting.

September 22, 2008

Response

1200ºC Is Too High

It has been pointed out that 3rd cycle fuel on the periphery of the core cannot achieve cladding temperatures of 1200ºC during a LOCA and that it would be overly conservative to use an ECR limit based on data at 1200ºC for that fuel. Although this statement may be correct, using the data in the RIL does not have to lead to an artificial limit on plant operation.

A Westinghouse paper at the 2004 NSRC concluded that <10% of the fuel in the core experiences rupture, even with uncertainties considered. If this paper is anywhere near correct, then a best-estimate licensing calculation would show that low-burnup peripheral fuel would not rupture. Peaking factors on the periphery are too low. Without rupture (PCT < 800ºC), the calculated ECR would be very low and there would be no penalty for this fuel.

Now think about 2nd or 3rd cycle fuel that is inboard where its peaking factor is high. Near the end of the cycle, this inboard fuel would have substantial burnup and contain much of its ultimate hydrogen content. Because of its high peaking factor, this fuel would approach a cladding temperature of 1200ºC and the current data would be entirely appropriate.

So you should be able to eliminate the extreme case, where there might be extra conservatism, and then focus on the highest burnup fuel in the core interior, where the present data are not conservative (they are our best estimates).

Background

Consider a case in which EOC 3rd cycle fuel has a hydrogen concentration of 800 ppm as permitted by Westinghouse specifications. For 2nd cycle fuel in this case, the PCT may approach 1200ºC because loading patterns and burnable poisons are designed to maintain uniform power levels for 1st and 2nd cycle fuel. Therefore, the current data are appropriate for this 2nd cycle fuel. This fuel in its 2nd cycle will have hydrogen concentrations of at least 400 ppm and therefore should be limited to an ECR of about 10%.

If the 200ºC reduction claimed by Westinghouse is correct for 3rd cycle fuel on the periphery (i.e., PCT = 1000ºC), one would calculate an ECR of about 3%. This is above the proposed limit at 800 ppm and would be limiting if no further consideration were made.

September 22, 2008

Response

Crud and Embrittlement

Crud will have some effect on heat transfer and hence on temperatures, and others can discuss heat transfer. Given the right temperature, though, crud should have little or no effect on oxidation and embrittlement.

Most crud components, such as iron, nickel, and copper, have small free energies of formation with oxygen and therefore will not get into the zirconium dioxide corrosion layer that is between the crud and the cladding. Chromium on the other hand might get into the oxide from the crud, just as some niobium gets into the oxide from the metal, and this could alter the oxidation rate at lower temperatures during a LOCA. Niobium reduces the oxidation rate.

If you get a little chromium in the corrosion layer, you might get a little chromium going into the metal from that layer during a LOCA, but this is not going to have any effect on embrittlement. Chromium, iron, and nickel are already minor alloying elements in these cladding materials, and we have found that embrittlement is insensitive to their concentrations. This is understandable because embrittlement is caused by oxygen diffusion in the metal, and this diffusion takes place by an interstitial mechanism. In a metal, this mechanism is not significantly affected by the impurity content, so you wouldn’t expect to see any effect of a few extra impurities that might find there way into the metal from the crud.

September 22, 2008

Response

Hydrided Balloons

Our goal was to determine burnup effects on embrittlement and see if an alloy-independent criterion could be used. We have done that. The balloon problem is not related to burnup or alloy. This is a problem that has been known for more than 25 years and we do not yet know how to handle it. In order to move forward and get a rule that will accommodate burnup effects and apply to a wide range of alloys, we propose to retain the *status quo* on the balloon until we can investigate it further with our integral tests. Maybe IRSN can help us with some of their data during the next two years that it will take to complete our tests.

September 19, 2008

Response

Linear Extrapolation

After using a zeroth-order correlation (a constant) for 35 years, a first-order fit to the sparse data set seemed appropriate. However, the concern seems to be that this straight line goes to zero at a hydrogen concentration (800 ppm) that probably exists in some high-burnup fuel.

We are in the process of making some more measurements on ZIRLO with different hydrogen levels, and we have some samples with hydrogen concentrations around 700 ppm. If we get enough data to put some curvature in the line, we might do it.

However, ANL's data at about 5% ECR never reached 1200ºC because we designed those tests to have prototypical heat-up rates. Those samples reached peak temperatures of only ~1185ºC and had an average diffusion temperature of only ~1150ºC. Look at Fig. 132 in the NUREG/CR for more information on temperatures. So the 5% value is not as conservative as has been suggested. Even if one got a non-zero ECR value at 800 ppm hydrogen in new tests, the ECR value would be very low. Therefore, waiting for more data is probably not going to solve the problem.

Fuel with 800 ppm hydrogen should probably be confined to the periphery of the core where it won't rupture and therefore will not oxidize significantly. If heavily hydrided fuel is loaded in the core interior, it may get hot and become brittle such that core coolability is no longer guaranteed.

September 22, 2008

Response

No Safety Issue

A claim has been made that the new experimental results do not indicate a significant safety issue. We acknowledged in the RIL that an evaluation of the safety significance was beyond the scope of the experimental program. Nevertheless, there is compelling evidence that an evaluation of the safety significance should be made.

There are many fuel rods in operating reactors that have corrosion layers of 30-40 microns in their 2^{nd} cycle and which consequently have hydrogen concentrations of ~400 ppm or more. Such rods should be limited to about 10% ECR (double sided) to preclude embrittlement following a LOCA. Although it is true that most plants that approach the current PCT limit of 1204ºC have corresponding calculated total oxidation of less than 17%, it is not at all clear that this calculated oxidation would always be less than 10%.

Such analyses need to be done with approved ECCS models to ensure public safety, and the only way to make sure an appropriate oxidation limit is never exceeded is through a change in 50.46(b)(2).

September 22, 2008

Response

Prehydriding as Surrogate

Of course it would be convenient if prehydrided unirradiated cladding could be used in testing as a surrogate for irradiated cladding. This might be useful in some future situation although we don't need any further testing of this type to write a good rule right now.

It is very likely that prehydrided material could be used as a surrogate for testing ductility under LOCA conditions. After all, hydrogen appears to be the dominant variable in all the testing we have done with irradiated cladding. Further, Fig. 148 in the NUREG/CR compares ductility for some prehydrided and irradiated material. To my eye, the results for prehydrided samples look less ductile than the irradiated ones, but the comparison is not bad.

The down side of such a comparison is that you cannot get the same varied hydrogen distribution in prehydrided material as we find in irradiated material. Further, there could be some irradiation damage that doesn't anneal out, although we expect that to be small.

In my opinion, results with prehydrided material could be used for determining trends and differences. But I would not accept them for absolute values until further calibration has been done. We are doing some additional embrittlement tests with irradiated ZIRLO that would yield a good range of hydrogen results for such a calibration. However, we do not plan to do enough testing with prehydrided ZIRLO to obtain a calibration. We do not need such results for rulemaking, and we view such calibration as providing a convenience that the industry should pay for.

September 22, 2008

Backup Slides

LOCA RIL-0801

Ralph Meyer
September 24, 2008

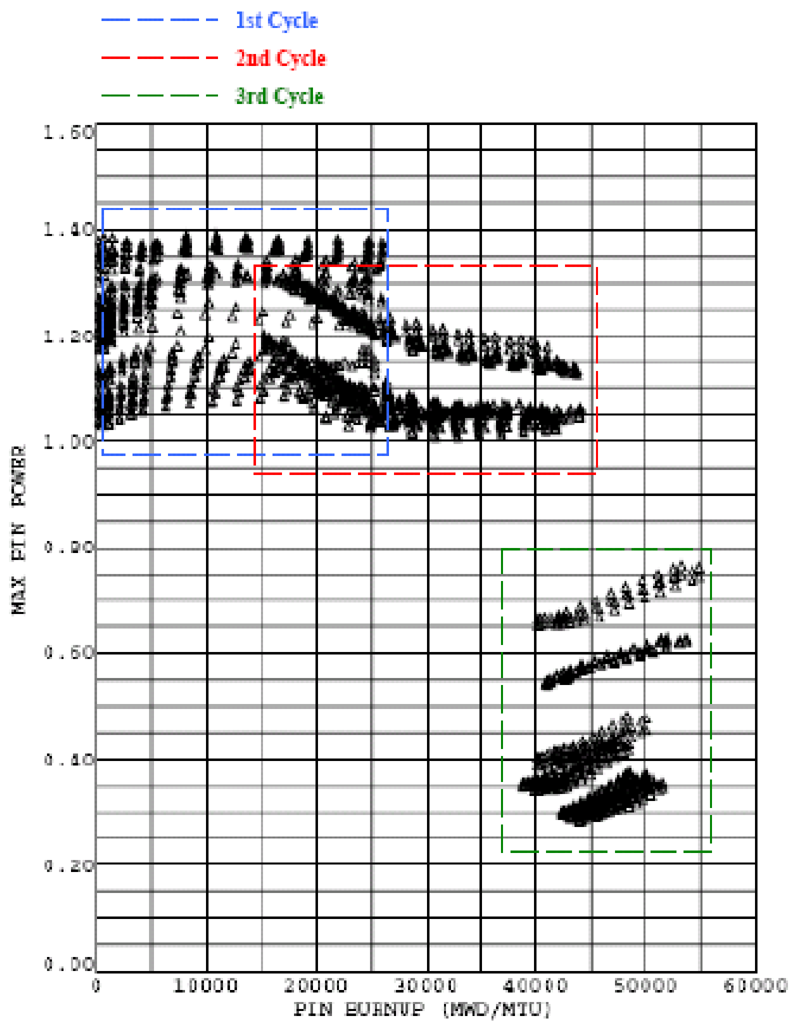
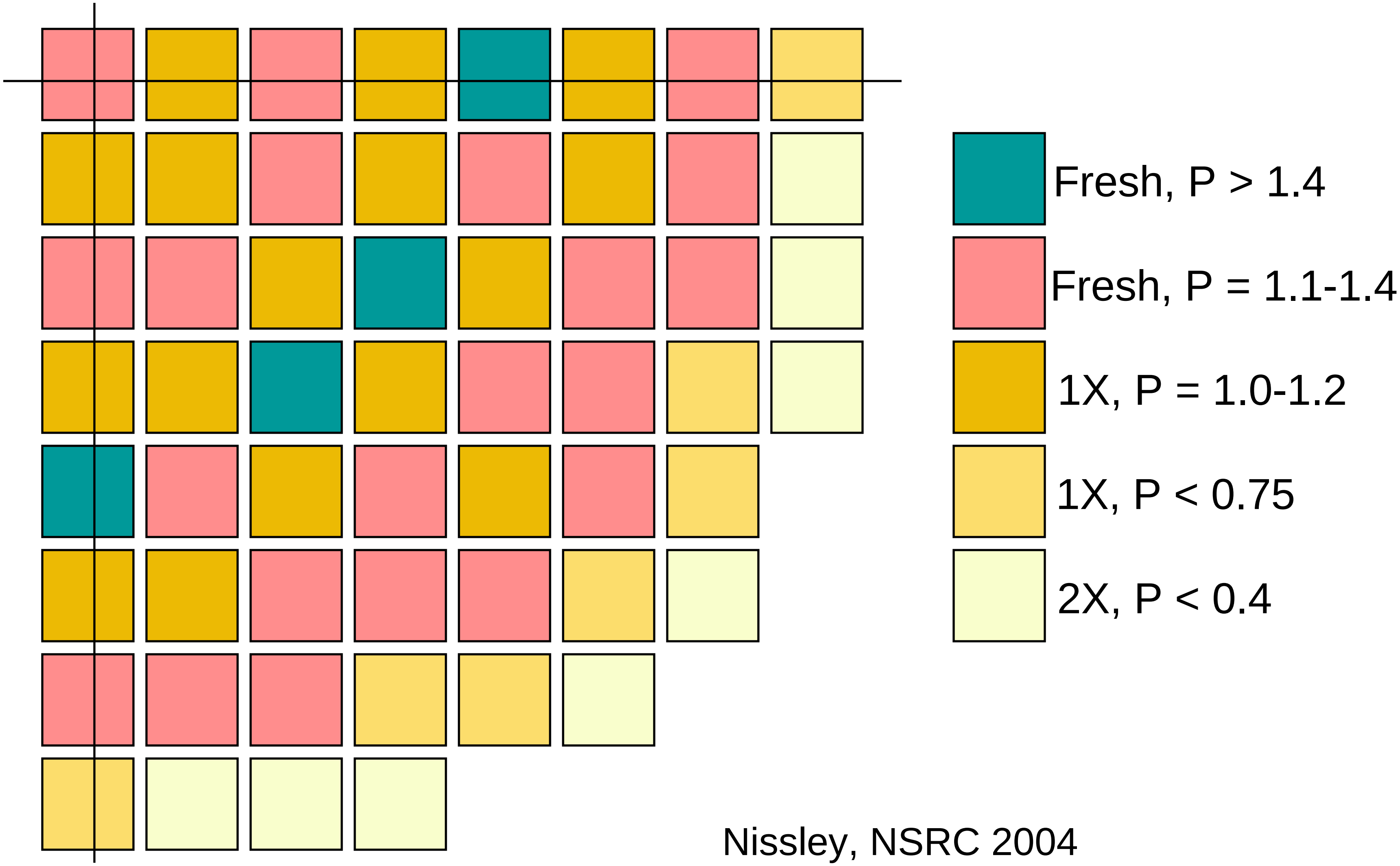
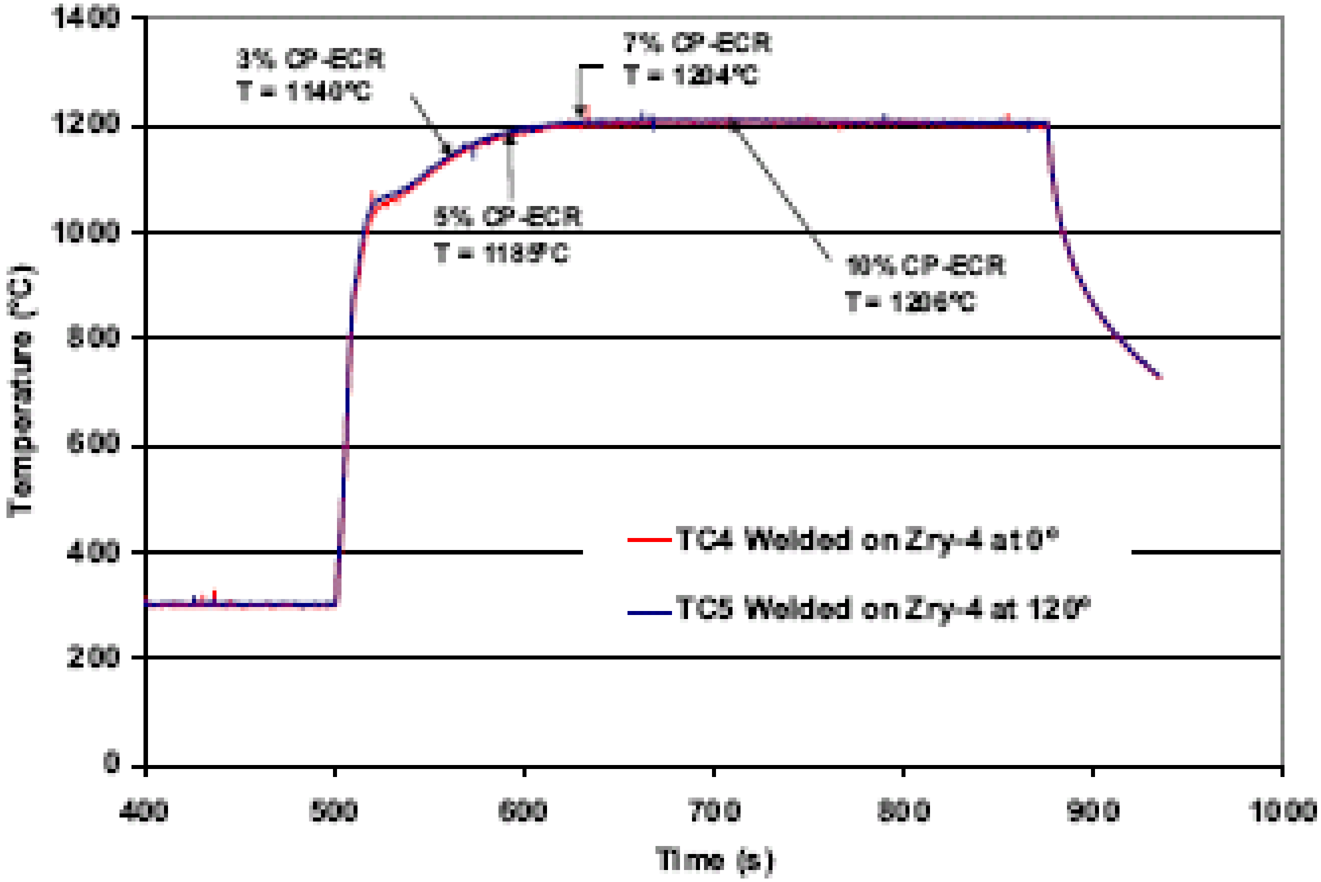


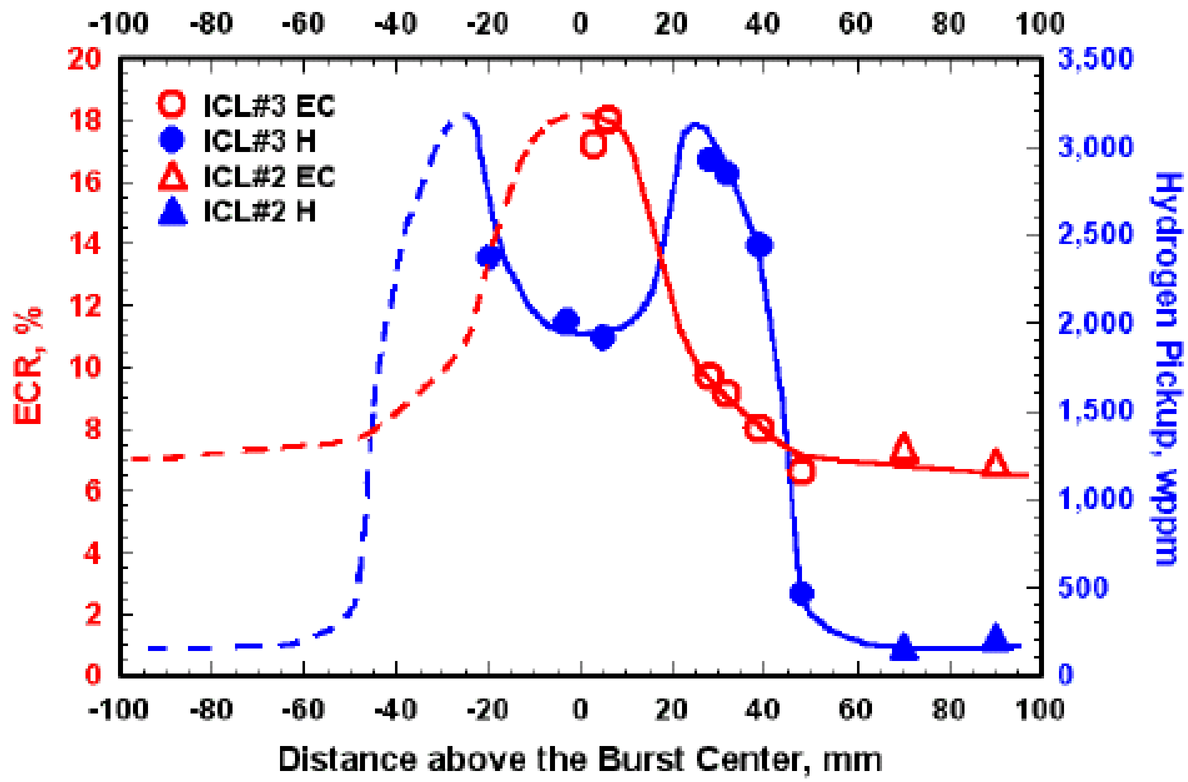
Figure I-1. Achievable Pin Power vs. Burnup for Typical Westinghouse 3-loop PWR

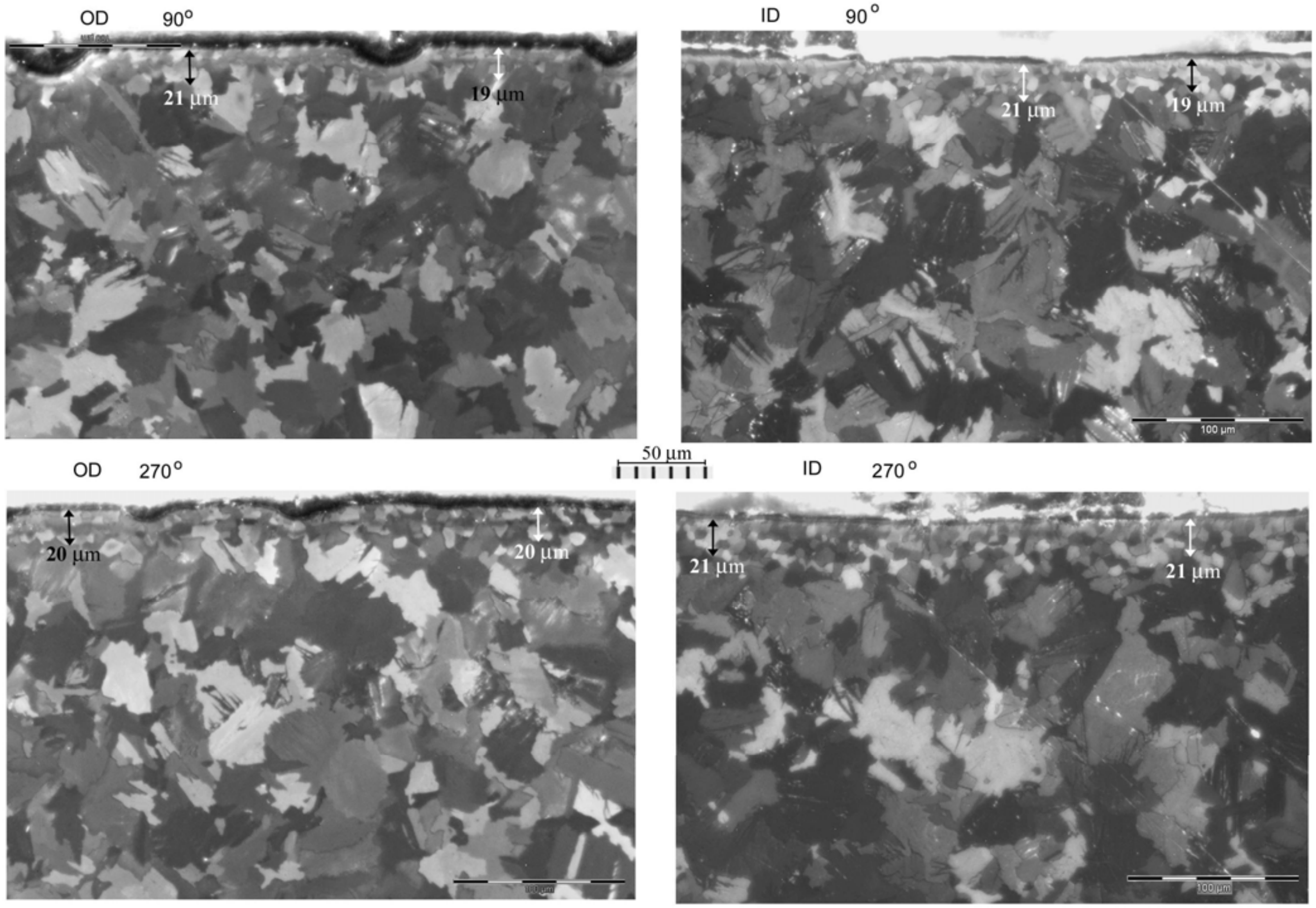
Assembly Power Distribution (Limiting BU)

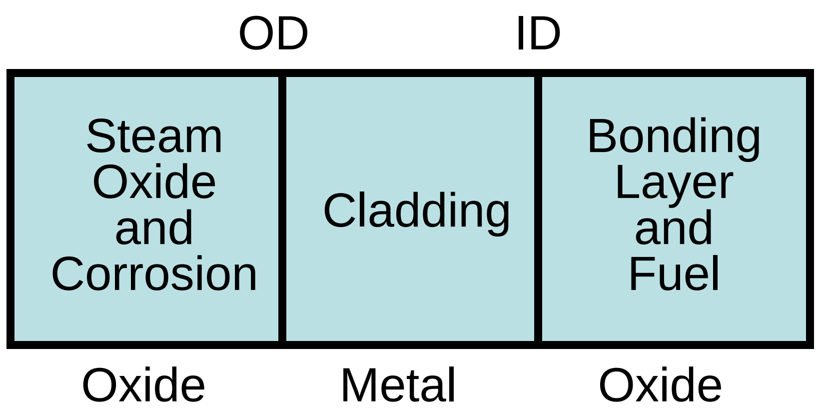


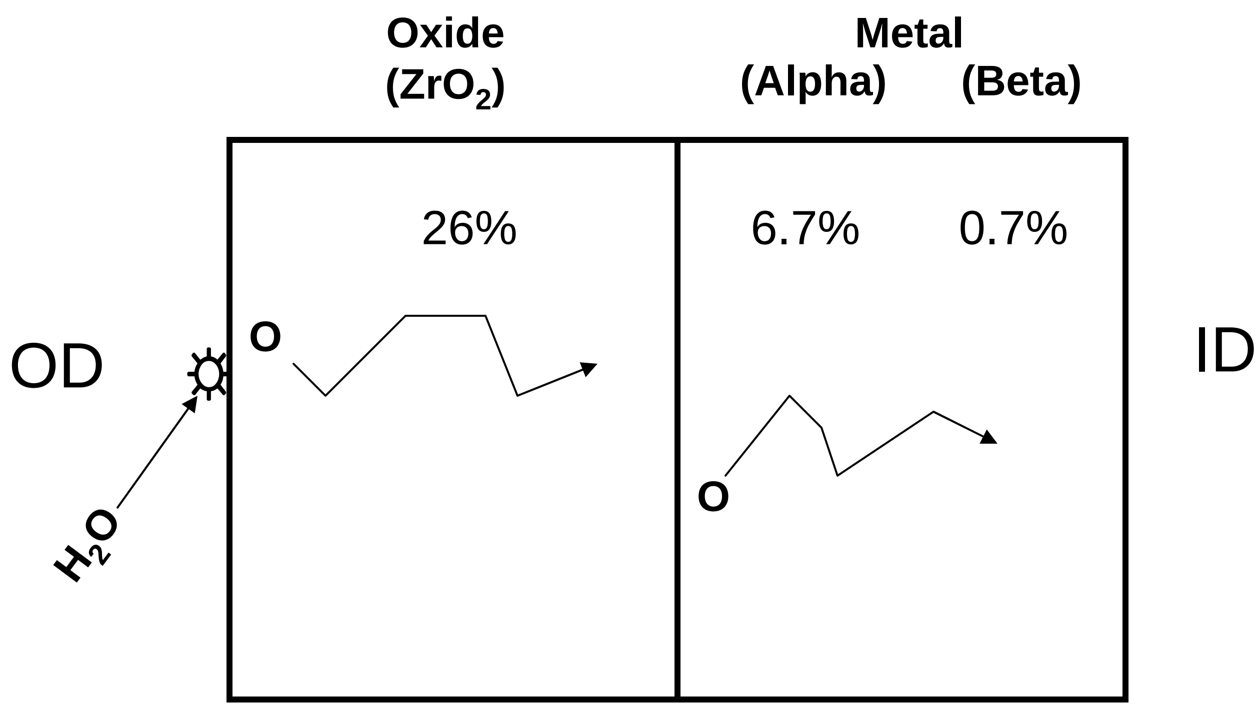
Nissley, NSRC 2004


3% CP-ECR
T = 1140°C
7% CP-ECR
T = 1204°C
5% CP-ECR
T = 1185°C
10% CP-ECR
T= 1206°C
TC4 Welded on Zry-4 at 0°
TC5 Welded on Zry-4 at 120°
Temperature (°C)
Time (s)
0
200
400
600
800
1000
1200
1400
400
500
600
700
800
900
1000


ICL#3 EC
ICL#3 H
ICL#2 EC
ICL#2 H
ECR, %
Hydrogen Pickup, wppm
Distance above the Burst Center, mm
-100
-80
-60
-40
-20
0
20
40
60
80
100
0
2
4
6
8
10
12
14
16
18
20
0
500
1,000
1,500
2,000
2,500
3,000
3,500


OD 90°
21 µm
19 µm
ID 90°
21 µm
19 µm
100 µm
50 µm
OD 270°
20 µm
20 µm
ID 270°
21 µm
21 µm
100 µm


OD
ID
Steam Oxide and Corrosion
Cladding
Bonding Layer and Fuel
Oxide
Metal
Oxide



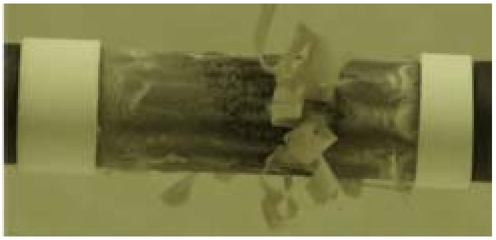
Ionic Crystal

Charge Neutrality Required
Nb is "aliovalent"

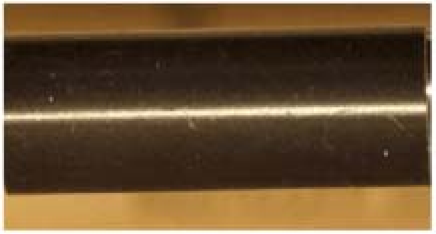
Metallic Crystal

Electron Cloud
Nb just like the others

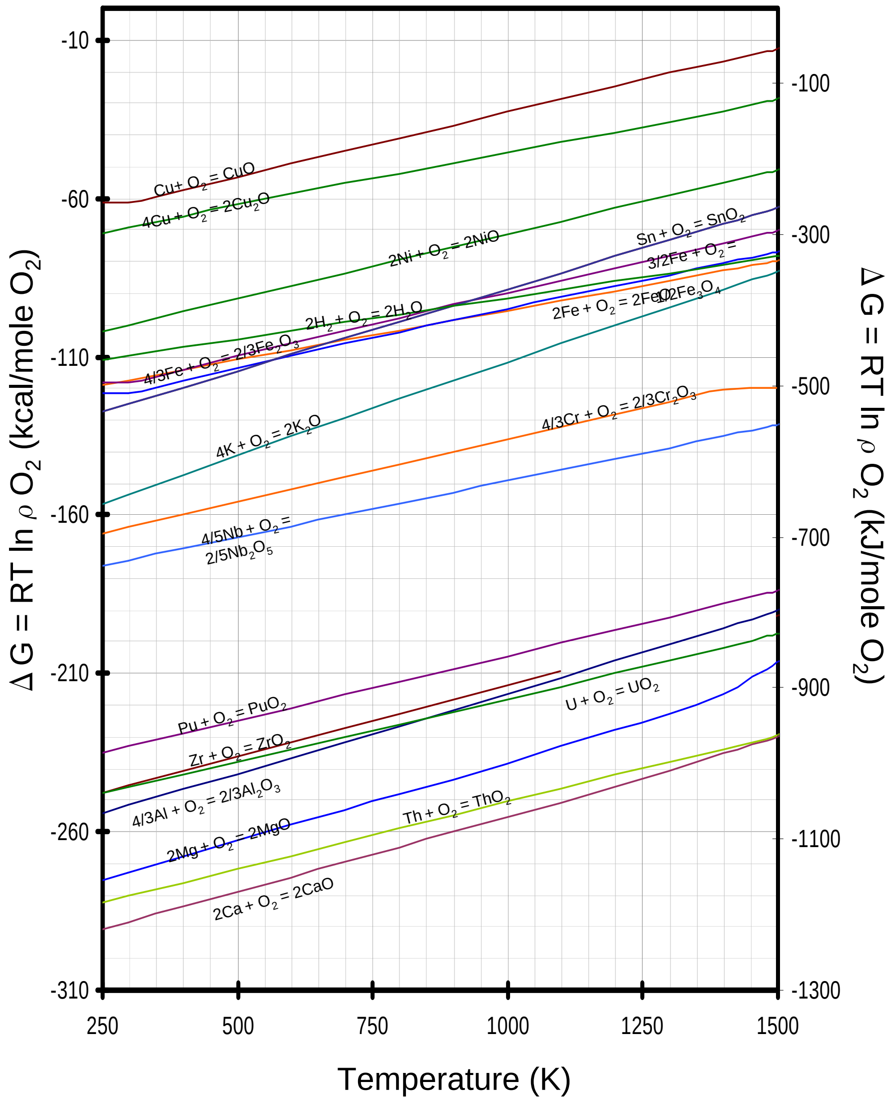
E110, 290 sec



E110, 1400 sec



M5, 2400 sec



$\Delta G = RT \ln \rho O_2$ (kcal/mole O_2)
$\Delta G = RT \ln \rho O_2$ (kJ/mole O_2)
Temperature (K)
-10
-60
-110
-160
-210
-260
-310
-100
-300
-500
-700
-900
-1100
-1300
250
500
750
1000
1250
1500
$Cu + O_2 = CuO$
$4Cu + O_2 = 2Cu_2O$
$2Ni + O_2 = 2NiO$
$Sn + O_2 = SnO_2$
$3/2Fe + O_2 = 1/2Fe_3O_4$
$2Fe + O_2 = 2FeO$
$2H_2 + O_2 = 2H_2O$
$4/3Fe + O_2 = 2/3Fe_2O_3$
$4K + O_2 = 2K_2O$
$4/3Cr + O_2 = 2/3Cr_2O_3$
$4/5Nb + O_2 = 2/5Nb_2O_5$
$Pu + O_2 = PuO_2$
$Zr + O_2 = ZrO_2$
$U + O_2 = UO_2$
$4/3Al + O_2 = 2/3Al_2O_3$
$2Mg + O_2 = 2MgO$
$Th + O_2 = ThO_2$
$2Ca + O_2 = 2CaO$