United States Nuclear Regulatory Commission

ACCEPTANCE CRITERIA AND METAL-WATER REACTION CORRELATIONS

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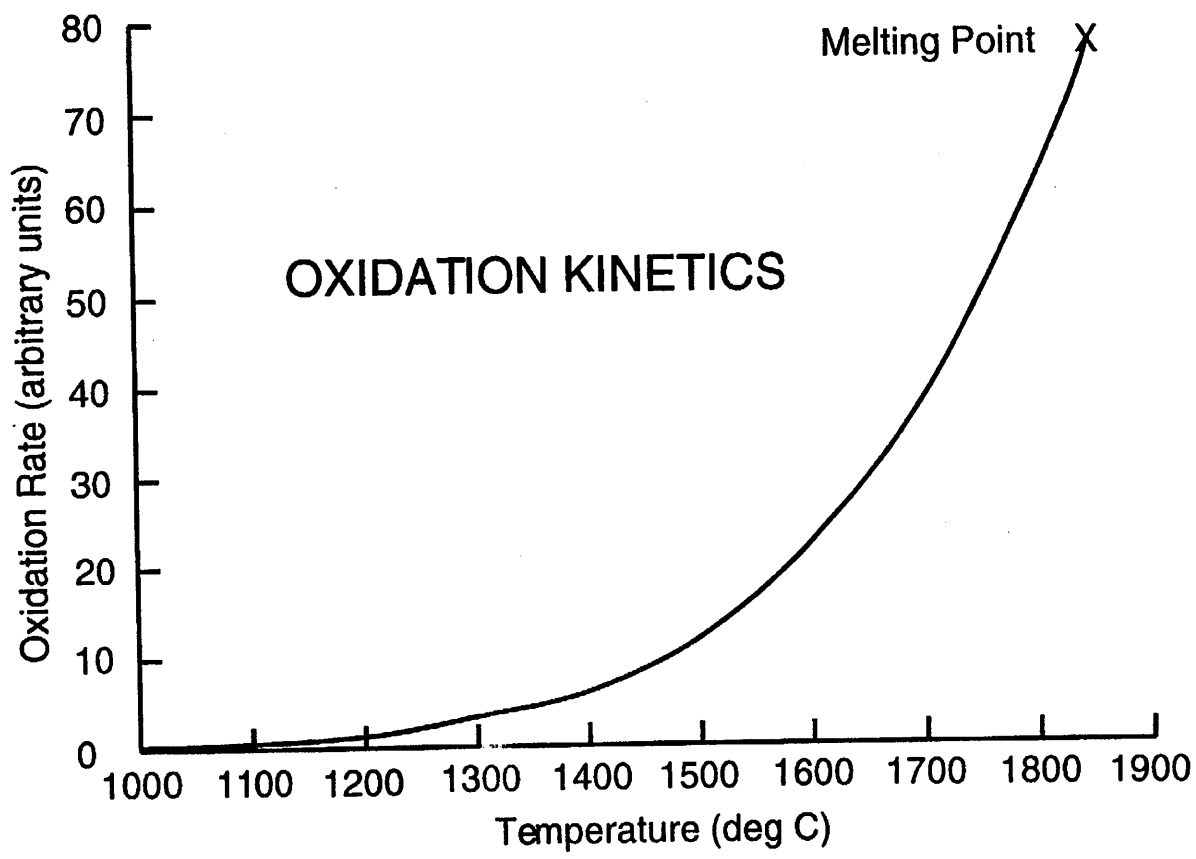
Public Meeting
June 28, 2002

ORIGIN OF PEAK CLADDING TEMPERATURE LIMIT

- Comes from temperature at which 17% ECR limit breaks down
- There was a second consideration related to runaway temperature escalation

STATEMENT ON TEMPERATURE LIMITS FROM 1973 HEARING

Westinghouse proposed a maximum calculated temperature limit of at least 2700°F; Combustion Engineering and the Utility Group agreed on 2500°F as the peak allowable calculated temperature on the basis that much of the data on oxidation and its effects stops at 2500°F. Babcock and Wilcox suggested a more conservative 2400°F as the peak calculated temperature to be allowed, presumably because "significant eutectic reaction and an excessive metal-to-water reaction rate would be precluded below 2400°F." General Electric argued strongly that the limit should not be reduced to 2200°F; that 2700°F is really all right as far as embrittlement is concerned, but that the Interim Acceptance Criterion value of 2300°F should be retained. In addition to being consistent with their expressed desire not to change any of the criteria, the GE recommendation of retaining the 2300°F limit is intended to ensure that the core never "gets into regions where the metal-water reaction becomes a serious concern." (Ref. 1, p. 1097)


OXIDATION KINETICS
Melting Point
Oxidation Rate (arbitrary units)
0
10
20
30
40
50
60
70
80
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
Temperature (deg C)

HEAT GENERATION RATE

- When reaction heat becomes a significant part of total, positive feedback may cause runaway

$$\text{Heat Rate}_{B\text{-}J}(2200°F) = \text{Heat Rate}_{C\text{-}P}(2307°F)$$

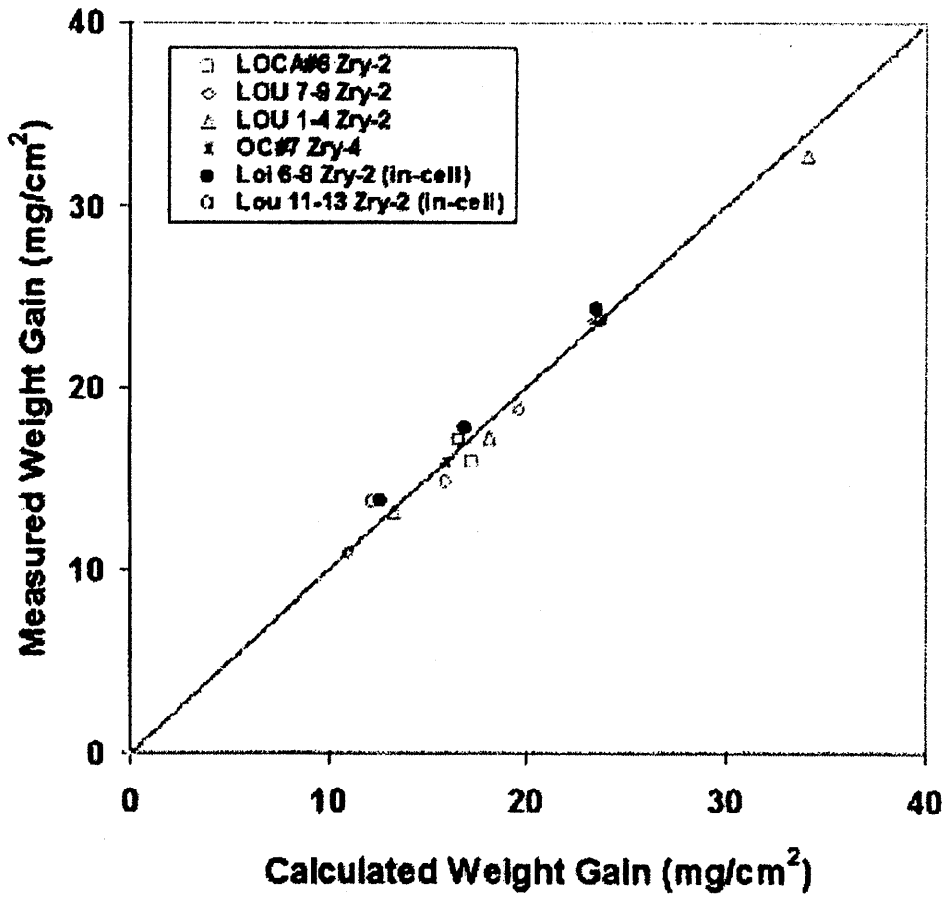
- Because Cathcart-Pawel is accurate, PCT could be increased to 2300°F with same margin to runaway as perceived in 1973

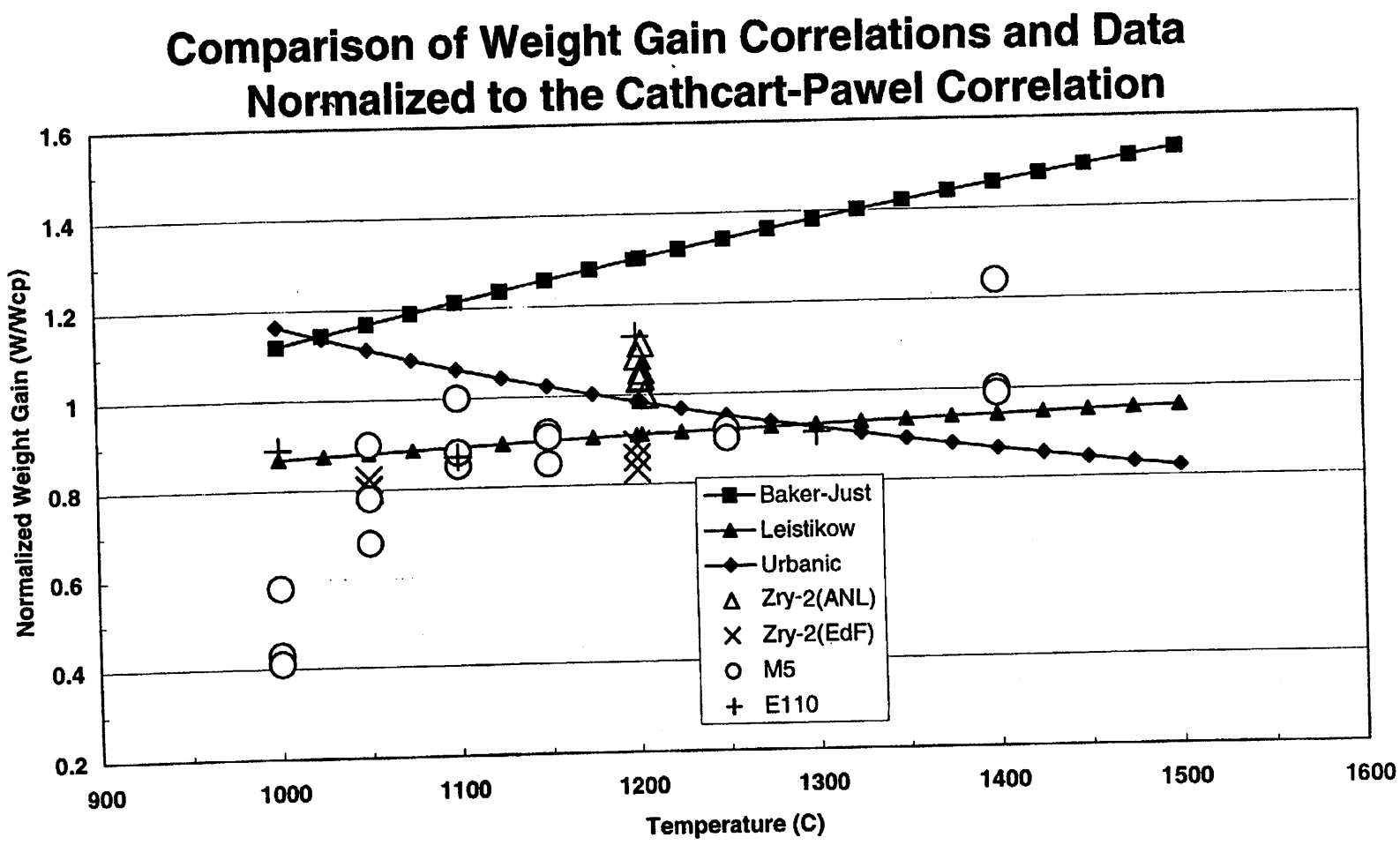
HIGH-TEMPERATURE OXIDATION MEASUREMENTS

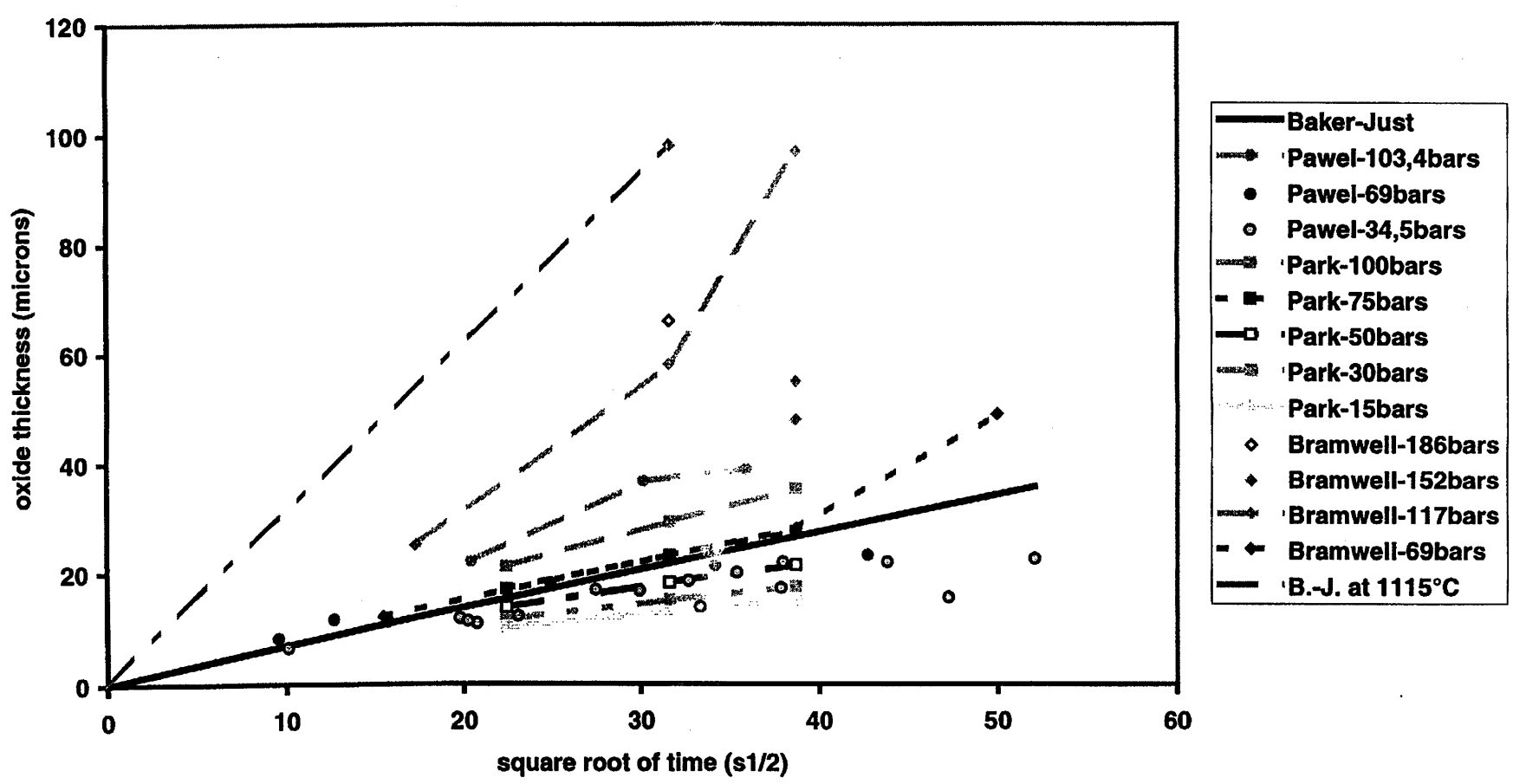
(Approximately the same rate around 2200°F)

Investigators	Metal
Baker and Just	Zr
Lemmon	Zr
White	Valoy (Zr-1.3Cr-0.1Fe)
Urbanic	Zircaloy-2, Zircaloy-4, Zr-2.5Nb
Cathcart et al.	Zircaloy-4
Chung and Kassner	Zircaloy-4
Grandjean et al.	Zircaloy-4
Yan et al.	Zircaloy-2
Waeckel and Jacques	Zircaloy-2
Le Bourhis	M5
Leech	ZIRLO
Yegorova et al.	E110 (Zr-1Nb)

Cathcart-Pawel model predictions vs. weight gain data for unirradiated Zry-2 and Zry-4 and high-burnup Zry-2 (Loi 6-8) exposed to steam for 5-40 min. at ≈1200°C



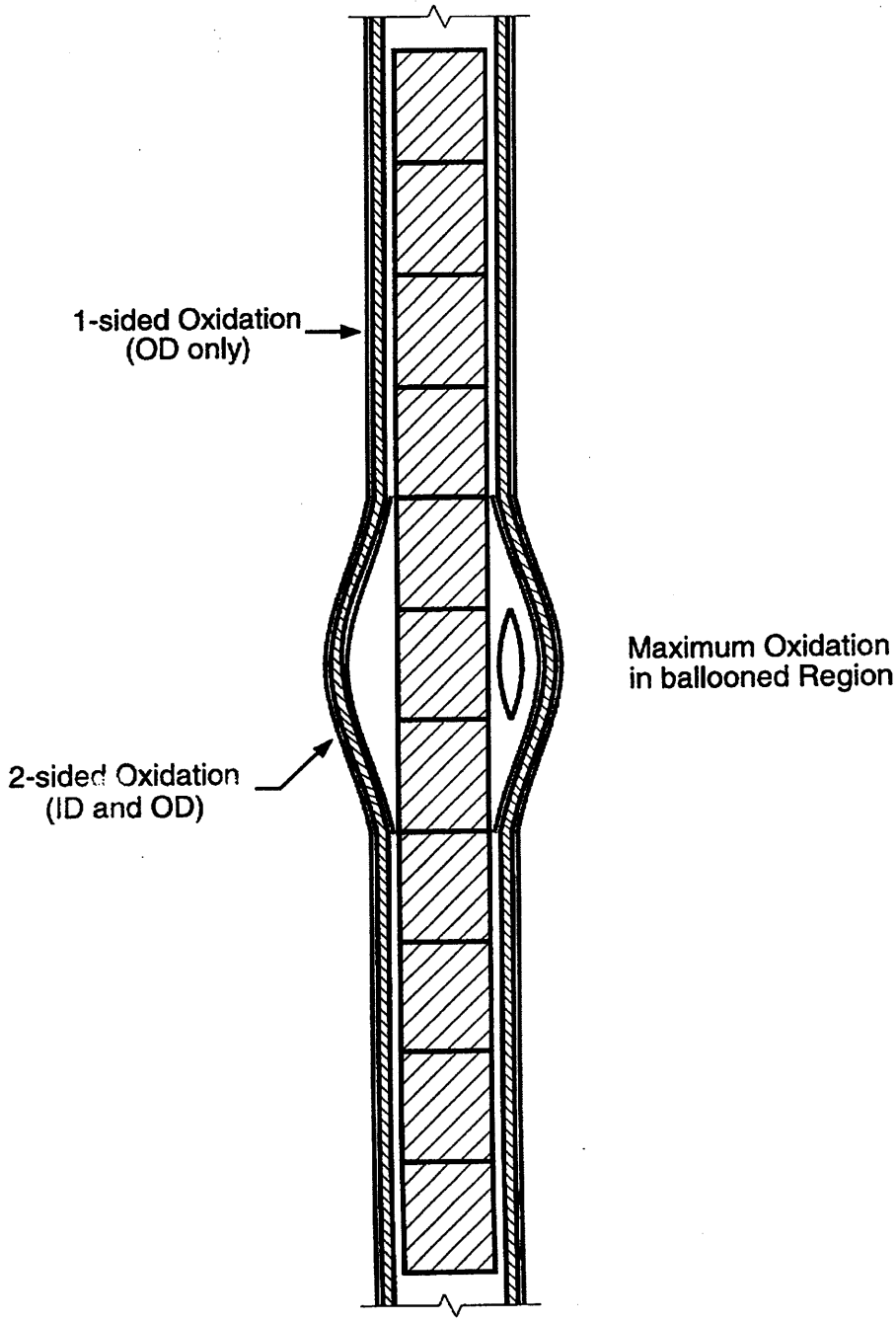

Comparison of Weight Gain Correlations and Data
Normalized to the Cathcart-Pawel Correlation
Normalized Weight Gain (W/Wcp)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
900
1000
1100
1200
1300
1400
1500
1600
Temperature (C)
Baker-Just
Leistikow
Urbanic
Zry-2(ANL)
Zry-2(EdF)
M5
E110


Zry - oxide thickness at 900°C as a function of square root of time and steam pressure
oxide thickness (microns)
square root of time (s1/2)
0
20
40
60
80
100
120
0
10
20
30
40
50
60
Baker-Just
Pawel-103,4bars
Pawel-69bars
Pawel-34,5bars
Park-100bars
Park-75bars
Park-50bars
Park-30bars
Park-15bars
Bramwell-186bars
Bramwell-152bars
Bramwell-117bars
Bramwell-69bars
B.-J. at 1115°C

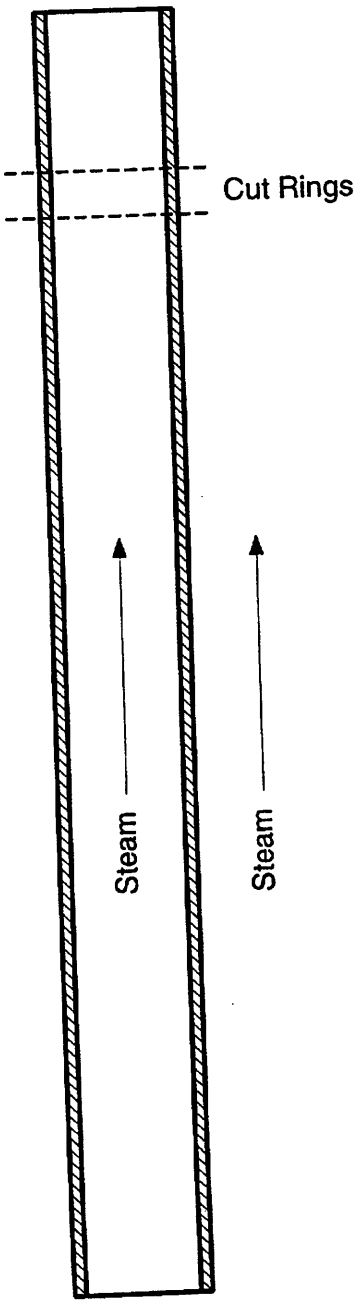
THERMAL SHOCK TESTS

Not adequate according to U.S. AEC Commissioners in 1973

"Our selection of the 2200°F limit results primarily from our belief that retention of ductility in the zircaloy is the best guarantee of its remaining intact during the hypothetical LOCA. The stress calculations, the measurements of strength and flexibility of oxidized rods, and the thermal shock tests all are reassuring, but their use for licensing purposes would involve an assumption of knowledge of the detailed process taking place in the core during a LOCA that we do not believe is justified."



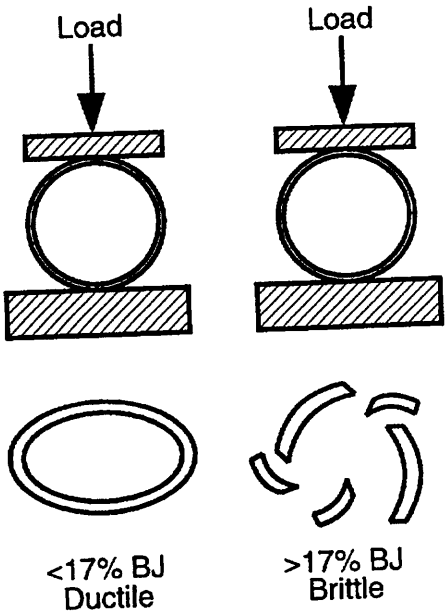
Significant Oxidation 1000 - 1200 C
(2200 F = 1204 C)



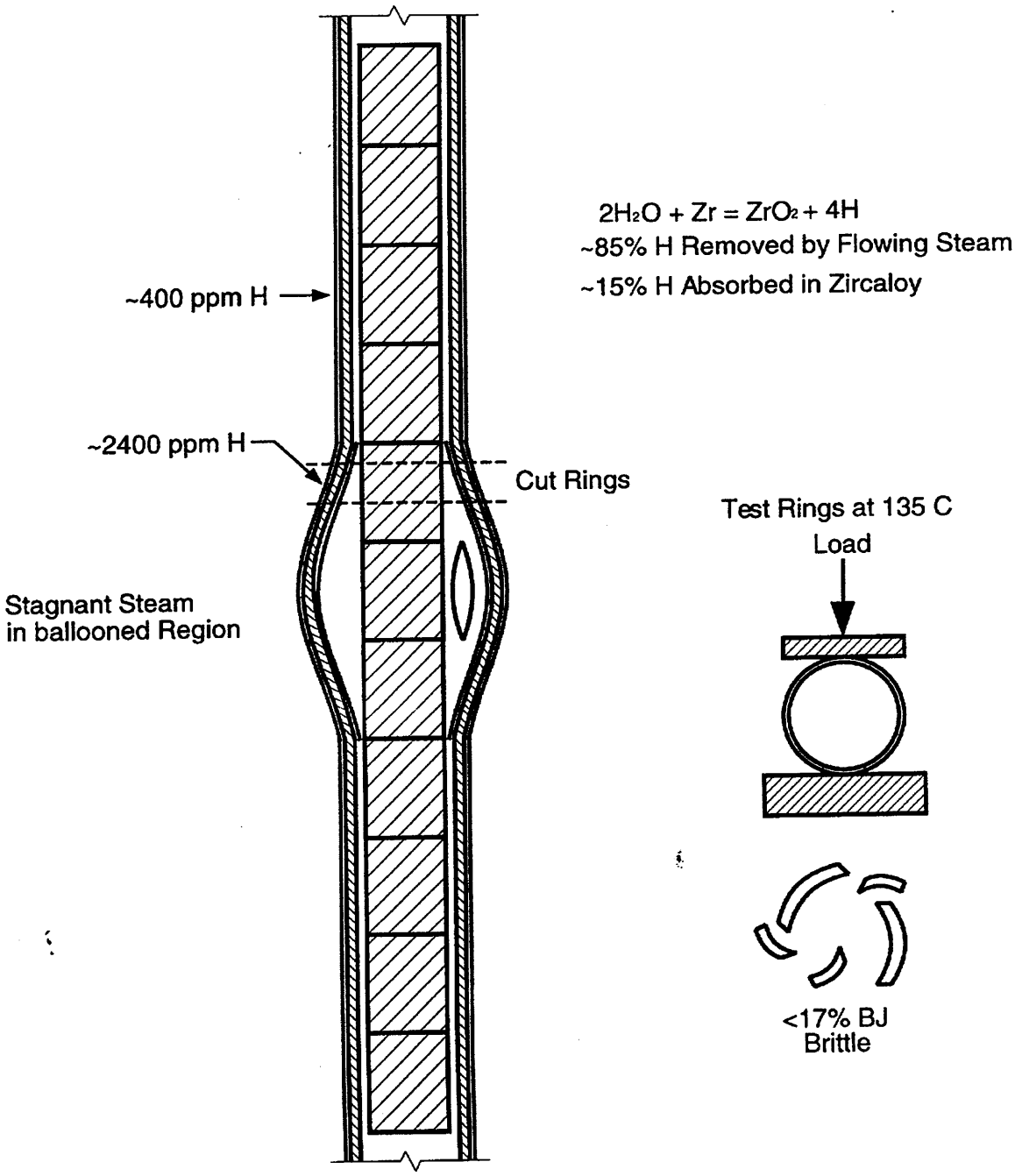
Oxidize at 1000 - 1200 C

Zircaloy
(Zr+1.5%Sn)

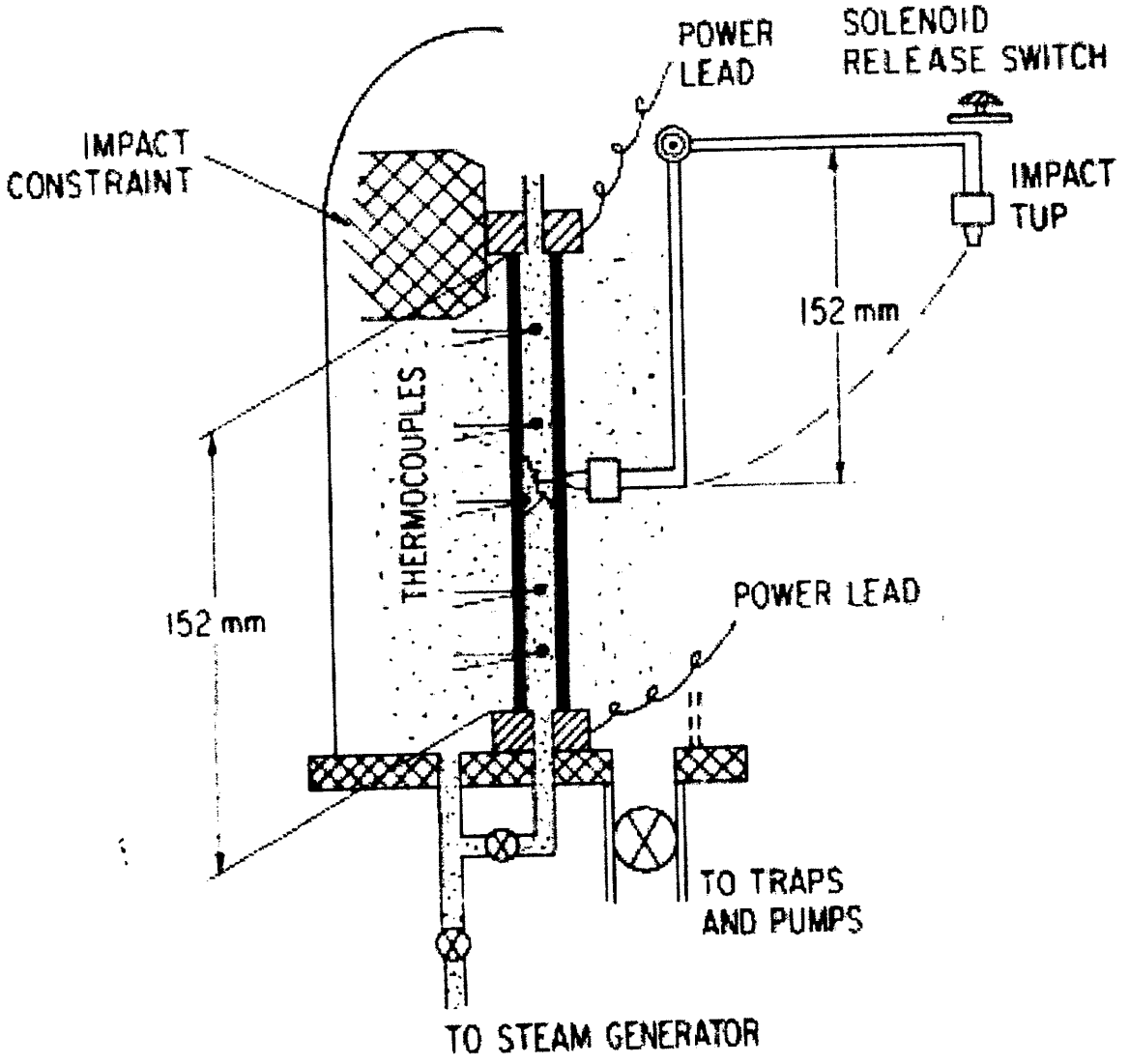
Test Rings at 135 C

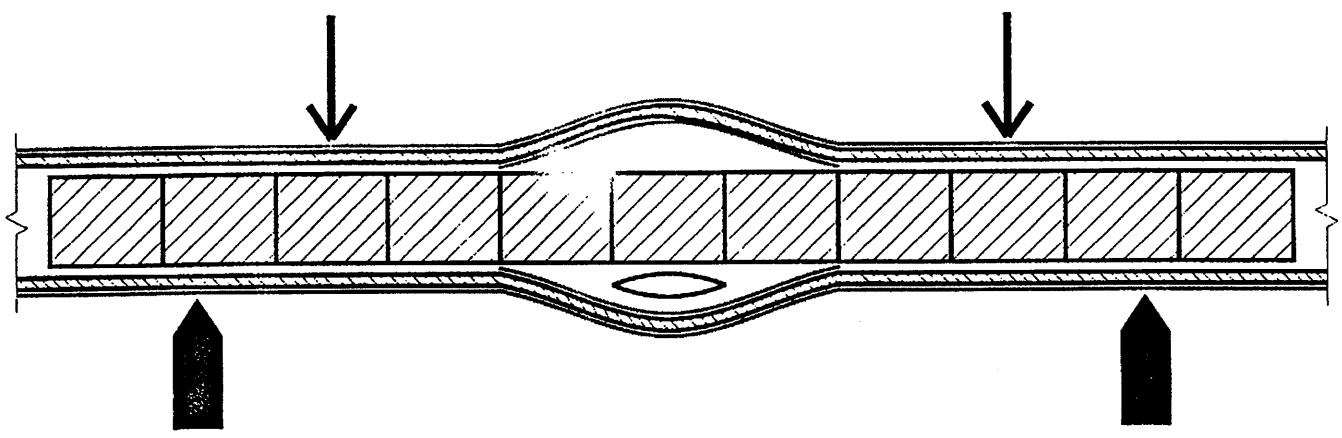


BJ = Total Oxidation Calculated with Baker-Just Correlation



Hydrogen Effect Discovered ~1980


POWER
LEAD
SOLENOID
RELEASE SWITCH
IMPACT
CONSTRAINT
IMPACT
TUP
152 mm
THERMOCOUPLES
152 mm
POWER LEAD
TO TRAPS
AND PUMPS
TO STEAM GENERATOR



4-Point Bend Test

CONCLUSIONS

- New PCT and ECR limits can be derived from mechanical property tests for all burnups and different alloys
- Simple ductility test (ring compression) may be adequate, as shown for unirradiated Zircaloy
- Confirmation of ductility test to be investigated with 4-point bend test
- PCT should not exceed 2300°F to retain margin to avoid runaway temperatures
- Cathcart-Pawel may work adequately for all alloys and burnups (TBD) provided pressure enhancement is added for SBLOCA analysis