50-320 NRR

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1 of 4

13 April 1979

ATTACHMENT #1

To: D. C. Ditmore

From: P. W. Marriott

Subject: MECHANICAL CONDITION OF THREE MILE ISLAND CORE

On April 12 the Industry Advisory Group (IAG) requested an independent judgment of the mechanical condition of the Three Mile Island (TMI) core, assuming a sequence of events regarding core cooling postulated by experts in the IAG. A summary of that information, as I understood it from you in our telecon, is presented in Attachment A. This memo conveys our judgment for your use in comparison to others'. It has not been subjected to independent, internal review: I leave it to you to handle it accordingly and to put it in proper perspective.

Core Heatup. With the limited and speculative nature of the sequence of events postulated in Attachment A, we have simply assumed adequate cooling (clad temperature at saturation) through 116 minutes, followed by convective cooling to superheated steam until quenching. Thermal radiation of peripheral rods to the core barrel would be significant for those rods, but insignificant to the central region of the core except insofar as it would abet natural circulation of steam within the core. Our judgment, unsupported by detailed calculations for this exact sequence, is that the cladding temperature would increase to at least 2600F under the flow conditions postulated by IAG, possibly higher. Assuming a limited amount of natural circulation of steam inside the vessel, the lower powered regions would be heated to similar temperatures.

For simplicity, our core mechanical considerations postulated a peak cladding temperature increasing linearly from 600F to 2600F from t = 116 minutes to t = 126 minutes, then holding constant at 2600F until quenching, with increasing amounts of cladding reaching 2600F through the transient. Quenching at t = 176 minutes would reduce cladding temperatures to saturation (~600F) in seconds. The five-minute heatup at t = 195 minutes is probably of secondary importance.

This postulation has the following limitations which may be important to the IAG's judgment of the mechanical condition of the core:

(1) It omits the possibility of early (t = 100 to 116 minutes) heatup, and perhaps cladding perforations, high in the core while good cooling is still taking place at lower elevations. An estimate of this could be made, if IAG's thermal-hydraulic advisers could speculate on vessel inventory and (even better) void distribution, during the first twenty minutes or so.

(2) It does not consider at what time the entire core would become essentially adiabatic and heat to higher temperatures. However, IAG's postulated event sequence, the heatup sequence we postulated, and IAG's estimate of 30-45% of the core's zircaloy reacted, all corroborate each other approximately.

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Roisman 79-98

Fuel Rod Perforation. Assuming a rod internal pressure of 400 psi at 20°C, the calculated rod internal pressure at ~2600°F is ~2320 psi. This yields a clad hoop stress of ~16,100 psi. Based on zircaloy rupture data the rods would be expected to balloon and perforate at cladding temperatures of ~1500°F.

Based on General Electric full-scale single-bundle ECCS heat transfer test data, the location of rod ballooning and perforation would be expected to be within ± 6 inches of the peak temperature region of the rod; the location on any given rod would be random within this range.

Assuming clad heatup from 600°F to ~2600°F in ten minutes and constant temperature thereafter, and using the Baker-Just rate equation, the clad wall could be expected to be about 47% oxidized in one-half hour, about 67% oxidized in one hour, and fully oxidized in about two hours. This calculation considers only external oxidation; the extent of oxidation can be expected to nearly double over a short length in areas where the rods have ballooned and perforated, exposing inner clad surfaces to an oxidizing environment.

Fuel Rod Ballooning. As noted above, for the rods experiencing the assumed elevated temperature and pressures imposed by the transient, rod ballooning would be expected. The maximum magnitude of the expected ballooning would be ~100%, i.e., the rod initial diameter would be expected to double. (This estimate is based on ANL 76-121 LWR Safety Research Program, Quarterly Progress Report July-September 1976). Based on full bundle tests conducted by GE and others, coplanar ballooning leading to extensive flow blockage would not be expected; however, as stated above, the ballooning would be expected to be preferentially located within roughly a one-foot section of the axial location of peak cladding temperature.

Fuel Rod Distortion. We cannot comment on the possibility of rod distortion or bowing during the core heatup because of our unfamiliarity with the core mechanical design. In GE full-scale ECCS heat transfer tests, some bowing of rods did occur at temperatures several hundred degrees lower than postulated here. It should be noted that the fuel rods in these tests had larger outside diameter and cladding thickness than TMI's. The possibility of rod distortion should be considered.

Clad Embrittlement and Effect of Quenching. Due to the clad heatup, significant oxidation would be expected. The brittle behavior of stabilized alpha-phase zirconium oxide would be expected to result in fragmentation under quench conditions. The 10CFR 50.46 oxidation limit to preclude this condition is 17% for LOCA application. ANL* has suggested a limit of 28% under slow quench conditions. It should be noted that in the experiments discussed by ANL, many of the rods which were intact following quenching failed during post-test handling. Post-test handling failure has also been experienced in fuel rods subjected to similar temperatures in tests performed by EG&G Idaho, Inc.

The posutlated amount of cladding oxidation and embrittlement, if present together with severe rod distortion, could have resulted in mechanical failure of affected rods during the heatup, quenching, or subsequent pressure or flow transients.

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* Argone National Laboratory, "Mechanical Properties of Zircaloy Containing Oxygen," USNRC Zircaloy Cladding Program Review Meeting, April 25-26, 1978.

Conclusions. Based on these scoping evaluations the following core mechanical condition is postulated:

(1) Rod ballooning leading to rupture expected in the highest-power areas of many or all fuel rods. Ballooning not expected to be coplanar.

(2) Clad perforation in many or all fuel rods resulting from operation past the rupture capability of Zr.

(3) Clad oxidation sufficient to cause fragmentation under quench conditions, particularly if aggravated by rod bowing.

PWMarriott

P. W. Marriott

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ATTACHMENT A

THREE MILE ISLAND-2 CORE HEATUP: POSTULATED SEQUENCE OF EVENTS

(Reference Telecon DC Ditmore to PW Marriott, 4/12/79, 1326 PST)

Time After Event, Min.	Event
100	"A" primary coolant pumps tripped ("B" pumps had been tripped previously)
100-116	Cooling by boiling in subcooled liquid and high-density froth
116	Density of fluid in core begins to decrease rapidly. Hot leg coolant temperature begins to show superheat.
116-146	Cooling by low density froth and (not much later) steam
146	Unexplained spike in core fluid density
146-176	No net inflow or outflow of steam in vessel (cooling by natural circulation of steam inside vessel)
176	Rapid quenching
176-195	Cooling by boiling in subcooled liquid and high-density froth
195-200	Brief second heatup
200	Rapid quenching

THREE MILE ISLAND-2 CORE HEATUP: CORE PRESSURE/TIME HISTORY

(Reference Telecon DC Ditmore to PW Marriott, 4/12/79, 1420 PST)

Time After Event, Min.	Core Pressure psig
60	1100
75	1045
90	1110
105	1000
120	800
135	670 (lowest)
150	800
165	1050
180	2200

4-12-79 J.W. Thiesing

Estimate of lower and median bound for $Zr-H_2O$ reaction

Basis: Inventory as of 4-1-79, 46,000 lbm Zr (Fuel clad only)

① H_2 burn - Now estimated to have released 2.5 - 4.0 X10^6 Btu
Equivalent to 2.5 - 4.0 % $Zr-H_2O$ rxn

② 2 v/o H_2 in containment 4-1-79
equivalent to 11.5 % $Zr-H_2O$ rxn

③ 1000 ft.³ bubble (1000psig/280°F) in RCS 4-1-79
equivalent to 13 % $Zr-H_2O$ rxn

④ Saturated RCS at 1000psig/280°F on 4-1-79 equivalent to 2.5 % $Zr-H_2O$ rxn.

⑤ Unknown degassing from 3-28 to 4-1 thru letdown system - could be equivalent to reduction in bubble from measured 1800 ft³ to 1000 ft³ on 4-1-79 equivalent to 10.5 % $Zr-H_2O$ rxn

Thus

Lower Bound = 29.5 %
①+②+③+④

Median estimate = 41.5 %
① → ⑤

CORE EXIT TEMPERATURE

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A															
B							286	287							
C						289			295	286			289		
D					288					286				286	
E				289			287		302		285				
F			294				252	205				285	282		
G		288			352	308			302		NG		286		
H	288				378			399	288				284		
K					296						305	285			
L		288	N.G.			314					286		N.G		
M			288				290		338	302				289	
N				291				300	293						
O					293	296				289		287			
P						295									
R							294			285					

t_{inlet} ~280°F

Core Decay Heat ~5MW

ATTACHMENT #4

CORE FLOW BLOCKAGE ASSESSMENT FROM CORE HEAT BALANCE

D. C. Ditmore
4/13/79

April 10, 1979 Reactor Conditions:

t_{core} in = ~ 280°F

t_{core} out = ~ 285 to 399°F (with two TC's reading below the core inlet and thus likely erroneous.)

$\overline{t}_{core}$ exit ~ 288.5°F in annular region outside very center of core
$(\Delta \overline{t}_{core} \sim 8.5°F)$

Q_{core} ~ 5MW

Normal operation - 4 pump core flow 137.9×10^6 lb/hr

Single loop - one pump core flow 1/8 - 1/4 x full core flow* (next page)

Unblocked Core Heat Balance - Single Loop/Single Pump

a) 1/8 of full core flow

$$Q_{core} = W_{core} C_p \Delta t_{core}$$

$$\Delta t_{core} \frac{Q_{core}}{C_p W_{core}} \qquad \frac{(5MW)\ (3.413 \times 10^6 \frac{BTU}{Hr.Min.})}{(137.9 \times 10^6\ lb/hr\ (\sim.9 \frac{BTU}{lb°F}} = \sim 1.1°F$$

b) 1/4 of full core flow

$$\Delta t_{core} \sim 2.2°F$$

Blocked Core (Current Condition) Heat Balance - Single Loop/Single Pump

$$(W_{core}\ C_p\ \Delta t_{core})_{unblocked} = (W_{core}\ C_p\ \Delta t_{core})_{blocked}$$

$$\frac{W_{core\,blocked}}{W_{core\,unblocked}} = \frac{(\Delta t_{core})_{unblocked}}{\Delta t_{core})_{blocked}} = \frac{A\ blocked}{A\ unblocked}$$

$(\Delta t_{core})_{blocked} \sim 8.5°F$

$(\Delta t_{core})_{unblocked} \sim 1\text{-}2°F$

$$\therefore \frac{A\ blocked}{A\ unblocked} \sim \frac{1\text{-}2°F}{8.5°F}$$ Range .11 - .24 ~ 89 - 76% flow blockage

89 - 76% core blockage in peripheral region

Because of high expectation that normal single pump operation core flow is closer to 1/8 of normal four pump operation core flow, the expected result is closer to 89%.

*Analyses by T. Mott and B&W indicate ~ 1/8 of the normal four pump flow through the core under one pump operation, most of the flow by-passing the core and flowing in reverse mode in non-operational loops.