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INFORMAL REPORT

ELECTROMATIC RELIEF VALVE FLOW AND PRIMARY SYSTEM HYDROGEN STORAGE DURING THE TMI-2 ACCIDENT

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ABSTRACT

Based on valve test data and theory of critical flow through an orifice, the flow history through the TMI-2 electromatic relief valve during the accident is calculated. The cumulative flow amounts to 8.0×10^5 kg based on the Wyle test data, about 20% below the inventory depletion estimated for the Borated Water Storage Tank during the accident. Based on pressure changes during a period of valve cycling before system depressurization and hydrogen venting to the containment, the hydrogen stored in the primary system is calculated to be about 450 kg, consistent with other estimates of total hydrogen generation during the accident.

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1. INTRODUCTION

The core-damage accident at the Three Mile Island, Unit 2 (TMI-2) nuclear reactor on March 28, 1979, can, in a certain sense, be attributed to the failure of an electromatic relief valve (ERV) on the top of the pressurizer of the primary coolant system. The valve failed in the stuck-open position and the resulting coolant loss from the primary cooling system was unrecognized for over two hours. Without adequate cooling, the reactor core experienced a high-temperature excursion. Hydrogen was generated in the core as the zircaloy cladding of the fuel reacted with steam. It was subsequently vented through the ERV to the containment. Fission products were also released from the fuel and they, too, found their way to the containment, mostly through the ERV. Therefore, to understand to details of the core-damage sequence, hydrogen generation, and fission products transport to the containment, one needs to quantify the operation of the ERV (opening and closing times) and estimate the loss of coolant from the ERV during the accident. This report documents some of the findings of such a study.

Section 2 presents an analysis of the flow test data on valves believed to be similar to the TMI-2 ERV. The analysis gives the effective discharge coefficients of the valves which are crucial to the accurate prediction of the flow rates. Section 3 gives the status of the block valve located upstream of the ERV. It was this valve that controlled the flow through the ERV during the accident. Section 4 estimates the flow through the ERV based on its characteristics, the block valve position, and the hydraulic conditions during the accident. This flow will provide a basis for calculating fission product transport rates to the containment. Through a simple observation of the pressure behavior during a period of regular block valve cycling, the hydrogen in the primary system is deduced. This is given in Section 5. The major findings of the study are summarized in Section 6.

2. ELECTROMATIC RELIEF VALVE DISCHARGE RATES

The ERV used in TMI-2 was manufactured by Dresser Industries. It carried the model number of 31533VX-30, but due to conflicting reports, the size of the flow orifice installed in the valve is uncertain. Table 1 summarizes the several references to the valve and the details are given below.

TABLE 1. CONFLICTING REPORTS ON THE TMI-2 ERV SIZE OR RELIEF CAPACITY

Source	Data
TMI-2 FSAR	
Table 5.1-2	112,000 lbm/hr
p. 5.5-11	118,909 lbm/hr
NSAC-80-1	100,000 lbm/hr 1-5/32-in. orifice
EPRI-NP-2628-SR	1-5/16-in. orifice

The TMI-2 Final Safety Analysis Report (FSAR) gave two references to the ERV flow rate, one in Table 5.1-2 as 112,000 lbm/hr (14.1 kg/s) saturated steam between open and closed design pressures of 2255 psig (15.65 MPa) and 2205 psig (15.30 MPa), respectively, and one as 118,909 lbm/hr (15.0 kg/s) on p. 5.5-11 in a paragraph describing the design bases of the Radwaste Disposal, Reactor Coolant Leakage Recovery System. NSAC 80-1 reported (Ref. 1, Appendix ERV. p. 1) a relief capacity of approximately 100,000 lbm/hr (12.6 kg/s) saturated steam through a 1-5/32 inch orifice at approximately 2255 psig (15.65 MPa). In the EPRI safety and relief valve test program, the ERV chosen for testing had the same Dresser model number of 31533VX-30, but with an orifice size of 1-5/16 inch (Ref. 2). The EPRI report (Ref. 2) identified the TMI-2 ERV as a Dresser valve with a model number of 31533VX-30 and an orifice size of 1-5/16 inch. In addition, the report gave a distribution of the usage of the Dresser valve of the same model number having various orifices as (valve size in inches, followed by the number of reactors, in parentheses, using that size) 1-3/32 (6), 1-5/32 (3), and 1-5/16 (11). Because the EPRI report came out later than the other reports and specifically addressed the relief capacities of valves used in nuclear power plants, the identification made in the EPRI report may be more reliable, but without substantiating information, the actual size used in TMI-2 remains uncertain.

Table 2 shows the EPRI valve test data. As mentioned earlier, the valves chosen for testing had the Dresser model number of 31533VX-30, with an orifice size of 1-5/16 inch. Ten valves were tested. Nineteen tests were reported with measured flow rates; two were steam tests at Marshall Steam Station, and the remaining 17 were steam and subcooled water tests at Wyle Laboratories. In all tests, the valves opened fully on actuation.

The critical mass flux, G_{crit}, given in Table 2 comes from an EG&G prepared computer program.[3] The critical flow models used in the program are the Homogeneous Equilibrium Model (HEM) for steam flow and the Henry-Fauske (HF) model for subcooled flow. The flow conditions (pressure P and temperature T) refer to stagnation conditions upstream of the flow orifice where the maximum (critical) mass flux occurs.

The area given in Table 2 is an effective flow area of the orifice of the test valve computed by dividing the measured flow rate by the critical mass flux (G_{crit}). Based on the Marshall steam tests (first two tests in Table 2), the effective area for steam flow is $(8.02 \pm 0.03) \times 10^{-4}$ m^2; based on the Wyle tests, it is $(6.87 \pm 0.11) \times 10^{-4}$ m^2. The discharge coefficient for subcooled flow, C_D, as listed in Table 2, is obtained by dividing the effective area for subcooled flow by the average effective area for steam flow based on the Wyle tests only. The average subcooled discharge coefficient thus obtained is 0.77 ± 0.04. The physical area based on the nominal 1-5/16 inch orifice is 8.73×10^{-4} m^2. If this nominal area is used for the flow area, the steam discharge coefficient is 0.919 ± 0.004 for the Marshall tests, 0.787 ± 0.013 for the Wyle Tests, and the subcooled discharge coefficient (Wyle tests only) is 0.60 ± 0.03.

The two sets of tests by Marshall and Wyle, taken by themselves, have relatively small spreads but the Marshall tests give about 16% higher steam flow rates than the Wyle tests. With these uncertainties in the results of

TABLE 2. EPRI DRESSER MODEL 31533VX-30 VALVE FLOW TESTS

	P (MPa)	T_{sat} (K)	T (K)	Flow (kg/s)	G_{crit}* (kg/m^2 - s)	Area ($10^{-4} m^2$)	C_D**
1.	15.82	619.6	619.6	19.54 (s)	24,315	8.04	--
2.	15.89	619.9	619.9	19.54 (s)	24,445	7.99	--
3.	16.24	621.7	626.5	17.27 (s)	24,876	6.94	--
4.	4.34	528.4	462.6	41.72 (ℓ)	73,884	5.65	0.82
5.	16.75	624.2	614.3	41.34 (ℓ)	75,170	5.50	0.80
6.	16.07	620.8	538.2	74.36 (ℓ)	133,727	5.56	0.81
7.	16.27	621.8	503.7	80.79 (ℓ)	150,924	5.35	0.78
8.	15.98	620.4	620.9	16.79 (s)	24,585	6.90	--
9.	16.70	624.0	617.6	37.21 (ℓ)	71.465	5.21	0.76
10.	4.77	534.1	507.0	33.12 (ℓ)	57,202	5.79	0.84
11.	16.00	620.5	508.7	78.49 (ℓ)	147,477	5.32	0.77
12.	4.56	531.4	320.4	49.00 (ℓ)	98,851	4.96	0.72
13.	16.62	623.6	616.5	38.11 (ℓ)	72,072	5.29	0.77
14.	16.27	621.8	608.7	41.74 (ℓ)	77,568	5.38	0.78
15.	15.83	619.6	615.4	16.33 (s)	24,333	6.70	--
16.	16.55	623.2	607.0	40.84 (ℓ)	80,856	5.05	0.74
17.	16.48	622.9	609.8	39.02 (ℓ)	77,933	5.00	0.73
18.	15.72	619.1	613.7	16.70 (s)	24,128	6.92	--
19.	16.55	622.9	608.2	39.93 (ℓ)	79,796	5.00	0.73

Note: First 2 tests from Marshall Steam Station, Terrell, NC (Duke Power Co.), others from Wyle Laboratories, Norco, CA.

* G_{crit} from Ref. 3.

** Based on average flow area (6.87×10^{-4} m^2) for steam from Wyle tests.

(s) = steam
(ℓ) = liquid

testing a specific type of valve, coupled with the uncertainty in the actual size of the TMI-2 ERV, one probably should not expect an accuracy of better than 20% in predicting the flow rate out of the TMI-2 ERV during the accident.

3. ERV BLOCK VALVE STATUS DURING THE TMI-2 ACCIDENT

The ERV (also referred to as the pilot-operated relief valve, power-operated relief valve, or PORV) in TMI-2 opened at its set-point of 2255 psig (15.65 MPa) a few seconds after the initiation of the accident and thereafter failed in the stuck-open position. Based on the EPRI tests, which showed that all the tested valves of the TMI-2 type opened fully upon actuation,[2] it is reasonable to assume that the TMI-2 ERV opened fully during the accident. After the opening of the ERV, flow through the ERV depended on the status of the block valve situated upstream of the ERV. During plant operation immediately before the accident, the block valve was in the open position. When it was recognized by the operators that the reactor was losing coolant through the ERV, the block valve was closed (about 139 min into the accident). Subsequently, the block valve was cycled open and closed many times for various reasons until it was closed permanently at about 795 min into the accident.

Table 3 is a history of the opening and closing of the block valve during the TMI-2 accident. The times listed are relative to the time of turbine trip. Except for the period from 343 to 455 min, when the block valve was undergoing rapid cycling, the times were obtained from the GPUN sequence-of-events report.[4] During the rapid block valve cycling period, the primary system pressure recorded on the reactimeter was used as a guide in determining the opening and closing times of the block valve. As shown in Figure 1, the serrated pressure curve leaves little doubt that the system pressure was responding to the opening and closing of the valve. The time when the pressure started to drop is identified as the time when the block valve was opened, and the time when the pressure started to rise is identified as the time when the block valve was closed.

The block valve open/closed history given in Table 3 is consistent with other published reports except for the period between 192 and 210 min. The table gives the GPUN version, which is consistent with the Rogovin report (Ref. 5, Vol. II, Part 2, Appendix II.2), but differs from the NRC's Office of Inspection and Enforcement (I&E) report (Ref. 6, Appendix I-A) and the NSAC report.[1] The I&E report noted that the block

TABLE 3. ERV BLOCK VALVE OPENING AND CLOSING TIMES

Opening Time (min)	Closing Time (min)	Interval (min)	Total Open Time (min)
.0	139.0	139.0	139.0
192.5	210.0	17.5	156.5
220.0	318.0	98.0	254.5
343.0	343.6	.6	255.1
345.5	346.0	.4	255.5
349.3	349.8	.5	256.1
350.5	352.5	2.0	258.0
356.0	357.0	1.0	259.0
359.1	360.4	1.3	260.3
362.3	363.8	1.4	261.7
366.5	367.9	1.4	263.1
370.0	371.4	1.4	264.4
374.0	375.5	1.4	265.9
377.3	378.7	1.4	267.3
381.1	382.5	1.5	268.7
384.7	385.9	1.2	269.9
387.9	389.2	1.3	271.2
391.1	392.3	1.3	272.4
394.4	395.6	1.2	273.6
397.7	398.9	1.3	274.9
401.1	402.7	1.6	276.5
405.0	406.2	1.2	277.7
408.2	409.6	1.4	279.1
411.7	413.1	1.4	280.5
415.5	416.9	1.4	281.9
418.9	420.3	1.5	283.3
422.5	424.1	1.5	284.8
426.1	427.1	1.0	285.8
429.9	430.6	.7	286.5
434.0	435.0	1.0	287.5
438.7	440.4	1.7	289.2
445.8	447.6	1.8	291.0
452.5	454.3	1.8	292.7
459.0	554.4	95.4	388.2
560.5	570.0	9.5	397.7
589.0	589.1	.1	397.8
601.0	672.0	71.0	468.8
754.5	763.0	8.5	477.3
772.0	795.0	23.0	500.3

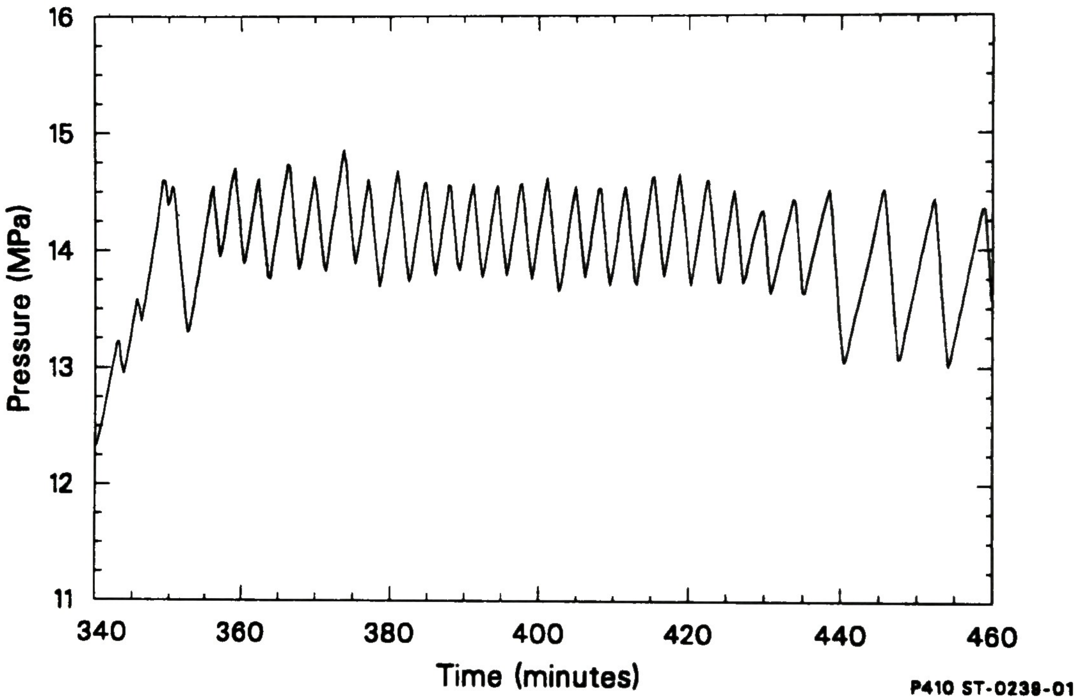

Figure 1. Primary coolant system pressure response to block valve cycling.

valve was opened at 193 min, closed 3 min later, and possibly cycled once before it was closed some time before 211 min. The NSAC report gave an opening time at 192.5 min and a closing time at about 197 min. These discrepancies apparently were caused by the difficulties associated with uniquely interpreting the containment temperature and pressure response, and also the pressure response of the reactor coolant drain tank (RCDT) into which the pressurizer effluent was discharged. Based on the pressure responses of the RCDT and the primary system, it was recently suggested[7] that two open and closed cycles occurred during this period: (1) 191.6 min open, 194.8 min closed, and (2) 197.9 min open, 198.4 min closed. For the purpose of calculating the discharge to the containment from the pressurizer, as documented in the next section, the history given in Table 3 was used. The uncertainty in the block valve open and closed times between 192 and 210 min does not materially affect the calculated total discharge from the pressurizer.

4. PRIMARY COOLANT LOSS FROM THE PRESSURIZER TO THE CONTAINMENT

During the EPRI tests,[2] all the electromatic relief valves of the TMI-2 type (Dresser Model 31533VX-30) opened fully on demand. Therefore, it may be assumed that the TMI-2 ERV on top of the pressurizer opened fully at the design set-point of 2255 psig (15.65 MPa) and failed in the fully open position. According to the plant piping diagram (Jersey Central Power and Light Co., Print 27615, Rev. 7), the line connecting the ERV to the pressurizer was a 2-1/2 inch, schedule 160 pipe (I.D. = 2.125" = 0.0540 m), and a block valve (a 2-1/2 inch motor-operated gate valve) was installed in this line to provide isolation if needed. Because the block valve flow area was more than twice that of the ERV (1-5/16 inch orifice, according to the EPRI Valve Test Report), the flow out of the pressurizer to the containment was limited to the critical flow rate through the ERV when both valves were open.

Figure 2 is a plot of the primary system pressure history from accident initiation to 900 min. To estimate the outflow through the ERV, sans a detailed hydraulic model, it was assumed that the flow rate was proportional to the square root of the primary system pressure (approximately the same as the pressurizer pressure) for a given temperature and void condition in the pressurizer just upstream of the ERV. As shown in Table 4, the outflow from the ERV was divided into several periods when the block valve was open. During each of these periods, the square root of the pressure was averaged over the time interval when the block valve was open.

For the periods after 343 min, measurements of the surge line or pressurizer temperature were available and the pressurizer water level was indicated full. (See Figures 12 and 13 in Ref. 7.) Therefore, it may be assumed that the condition upstream of the ERV was either subcooled or saturated with liquid, as indicated by the measurements.

The period from 220 to 318 min can be considered transitional in nature in that the fluid in the pressurizer could have changed from saturated steam to saturated liquid during this period. Emergency core

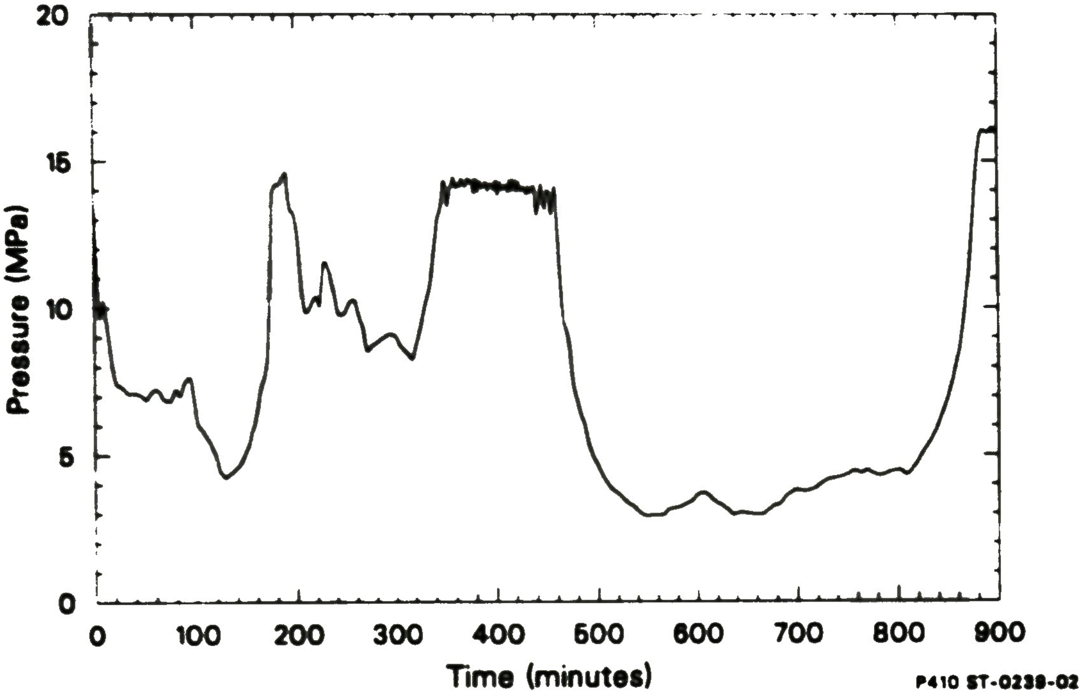

Figure 2. Primary coolant system pressure history.

TABLE 4. ESTIMATED OUTFLOW THROUGH THE ERV DURING THE TMI-2 ACCIDENT

Period (min)	Flow Time (min)	$(\overline{\sqrt{p}})^2$ (MPa)	T (K)	Void Fraction	G_{crit} (kg/m^2- s)	Rate* (kg/s)	Flow* (10^5 kg)
0-139	139.0	6.8	557 (sat)	0.7	20,157	13.85	1.155
192-210	17.5	11.9	597 (sat)	1.0	17,526	12.04	0.126
220-269	49	10.3	586 (sat)	1.0	14,976	10.29	0.302
269-318	49	8.8	575 (sat)	0	51,991	27.50	0.809
343-454	38.2	14.1	450	0	154,039	81.49	1.868
459-555	95.4	5.0	450	0	84,997	44.96	2.574
560-800	112.1	3.5	516 (sat)	0	33,017	17.51	1.178
							8.012

* To be consistent with inventory depletion in the Borated Water Storage Tank, the rate and the flow should be multiplied by 1.2.

cooling water was delivered to the primary coolant system under manual control of the operators from 220 to 267 min, but with two high-pressure injection pumps running only intermittently. From 267 to 318 min, two high-pressure injection pumps were in continuous operation, so it is likely that during this period the pressurizer was being filled with liquid. This hypothesis is supported by the pressurizer level indications which fluctuated on and off scale near the full-scale mark. It was assumed in this study that, during the first half of the period (220 to 269 min), the condition upstream of the ERV was saturated steam, and during the second half (269 to 318 min), it was saturated liquid water.

Before 200 min, it is believed that a negligible amount of emergency core coolant water was delivered to the primary coolant system, and the primary coolant inventory was near its lowest point immediately after the block valve closure at 139 min. When the block valve was believed open from 192.5 to 210 min, the indicated pressurizer level was less than full. Therefore, it is assumed that the condition upstream of the ERV during this period was saturated steam.

The assigned void fraction of 0.7 for the period 0-139 min shown in Table 4 is an inferred quantity based on the estimated primary coolant inventory loss. By 139 min, it is believed that some of the fuel rods ruptured due to heatup to 1200 K. Therefore, the water level in the core must have been at some distance below the top of the core. After the primary coolant pumps stopped running at about 100 min, the water must have settled in the lower part of the system, except in the pressurizer where the liquid was held up by continuous steam flow from the surge line. Between 100 and 139 min, water was boiled off in the core, replenished from the rest of the system, until the water level in the system dropped below the elevation of the inlet and outlet nozzles of the vessel. Therefore, the liquid inventory in the primary system, excluding the pressurizer, was limited to the volume below the nozzle elevation in the cold legs and steam generators, and approximately below the mid-core elevation in the vessel; the rest was lost from the system. If it is further assumed that the makeup flow was one-half of the letdown flow of 7.4 kg/s (120 gpm) (from Ref. 8), a total flow of approximately 1.2×10^5 kg through the ERV during the first 139 min is obtained. A void fraction of 0.7 just upstream of the ERV in the pressurizer would give the necessary flow out of the ERV during this period (et seq).

The computer program given in Ref. 3 was used to calculate the critical flow rates, G_{crit}, in Table 4 for the hydraulic conditions listed in the table. The flow rate is based on the Wyle results of a flow area of 8.73×10^{-4} m^2 (1-5/16 inch orifice), and discharge coefficients of 0.787 for steam and two-phase flow, and 0.60 for subcooled flow (upstream stagnation condition).

The total flow through the ERV during the accident is calculated to be 8.0×10^5 kg. It is about 20% lower than that estimated by others from volume changes in the Borated Water Storage Tank (BWST).[6,9,10] The total cumulative flow from the pressurizer through the ERV to the containment as a function of time and a comparison curve for the BWST inventory depletion (computed from values given in Table I.4-3 of Ref. 6) are shown in Figure 3.

If the discharge coefficients had been increased by 16% to match the Marshall steam flow test results, the total calculated outflow would have agreed very well with the inventory loss from the Borated Water Storage Tank, which supplied the emergency core coolant water.

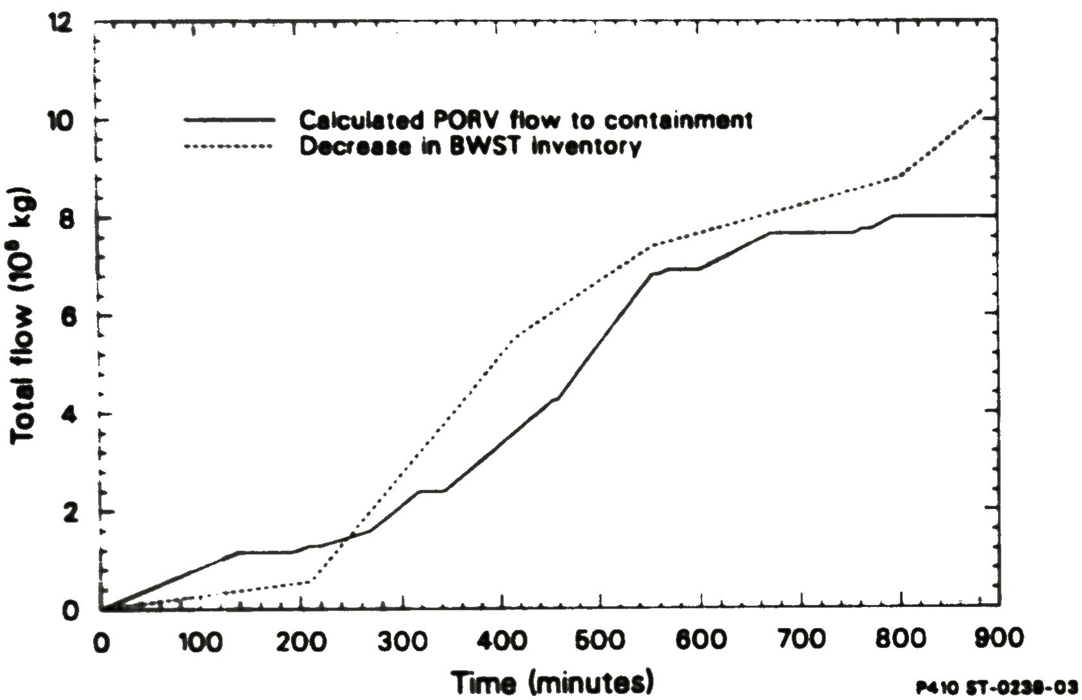

Figure 3. Cumulative mass flow from the primary coolant system to the containment compared to BWST inventory depletion.

5. HYDROGEN IN THE PRIMARY COOLANT SYSTEM

The regular cycling of the ERV block valve between 343 and 454 min provides a convenient means to estimate the amount of noncondensible gases in the primary coolant system during that period. The regular response of the primary pressure to the cycling of the valve suggests that the noncondensibles were trapped in the system, and the pressure changes were due to the compression and expansion of the gas bubbles in the system as the liquid volume in the system changed. The noncondensibles were mostly hydrogen generated from the steam-zirconium reaction.

Table 5 gives the primary coolant system pressure at the block valve opening and closing times between 380 and 420 min. During this time interval the pressure responses were especially regular, indicating a simple process of expansion and compression of a noncondensible gas. We assume that the process was isothermal and followed Boyle's law. When the block valve was closed, the liquid volume was increased as a result of the makeup, so the gas volume contracted. If we consider one pressure cycle, as shown in Figure 4, the constancy of liquid volume at the beginning and the end of the cycle (same system pressure) gives the following relationship between flow through the ERV when the block valve was open, and the makeup flow during the entire cycle:

$$F_o \Delta t_o = F_{in} (\Delta t_o + \Delta t_c)$$

where

F_o = outflow through the ERV

F_{in} = makeup flow

Δt_o = block valve open interval, and

Δt_c = block valve closed interval.

TABLE 5. PRIMARY SYSTEM PRESSURE CHANGES DURING BLOCK VALVE CYCLING, 380-420 MIN

Opening Time (min)	Pressure (MPa)	Closing Time (min)	Pressure (MPa)
381.1	14.68	382.5	13.71
384.7	14.62	385.9	13.74
387.9	14.57	389.1	13.79
391.1	14.56	392.3	13.72
394.4	14.56	395.6	13.74
397.6	14.57	398.9	13.75
401.1	14.62	402.7	13.60
405.0	14.54	406.2	13.72
408.2	14.55	409.6	13.65
411.7	14.52	413.1	13.67
415.5	14.67	416.9	13.75
418.9	14.66	420.3	13.54

Average open time = 1.33 min

Average pressure at opening time = 14.59 MPa

Average closed time = 2.12 min

Average pressure at closing time = 13.70 MPa

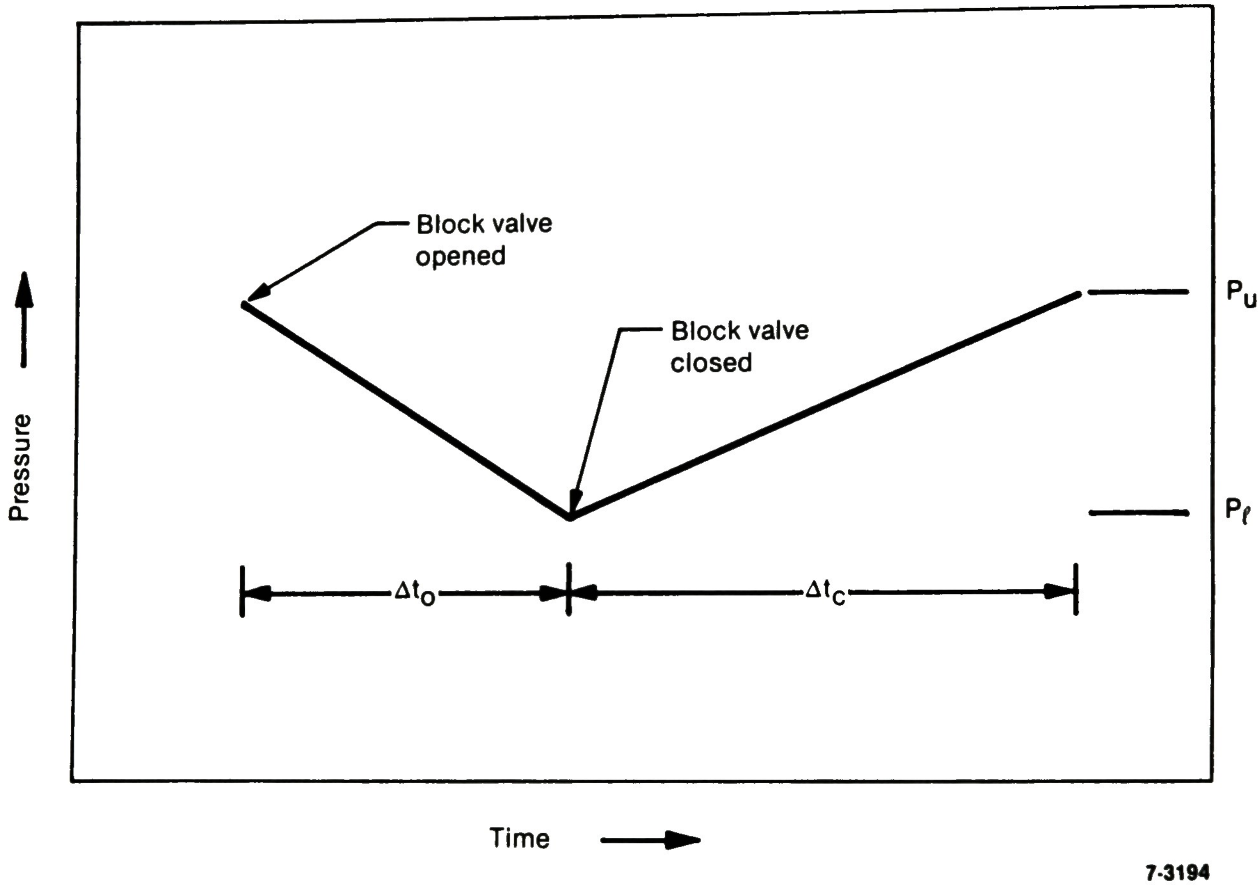

Figure 4. Illustration of primary coolant system pressure response during block valve cycling period.

From Table 4,

$$F_o = 81.5 \text{ kg/s}.$$

From Table 5, we use the average open and closed times,

$$\Delta t_o = 1.33 \text{ min}$$

$$\Delta t_c = 2.12 \text{ min}.$$

The makeup flow is therefore,

$$F_{in} = F_o \Delta t_o/(\Delta t_o + \Delta t_c) = 81.5 \times 1.33/(1.33 + 2.12) = 31.4 \text{ kg/s},$$

which is approximately 500 gpm. This makeup flow rate is about 20% lower than that calculated from the decrease in inventory in the Borated Water Storage Tank (640 gpm, p. I-4-20 of Ref. 6), similar to the underestimate of the calculated total outflow through the ERV when compared to the inventory decrease in the borated Water Storage Tank (see Section 4 of this report).

Let V be the total volume of the noncondensible gas (hydrogen) in the system and ΔV the decrease in volume when the gas was compressed. From Boyle's law, we have

$$\frac{\Delta V}{V} \approx \frac{P_u - P_\ell}{P_\ell} \quad ,$$

where

P_ℓ = pressure at block valve closure

P_u = pressure at block valve opening.

From Table 5,

$$P_u = 14.59 \text{ MPa}$$

$$P_\ell = 13.70 \text{ MPa}.$$

The change in volume, ΔV, is simply the liquid volume increase in the period when the block valve was closed, i.e.,

$$\Delta V = F_{in}\, \Delta t_c/\rho$$

$$= 31.4 \times 2.12 \times 60/900$$

$$= 4.44 \text{ m}^3.$$

We have used 900 kg/m^3 as the liquid density, ρ, at 14 MPa and 450 K.

The total hydrogen volume is

$$V \approx \frac{P_\ell\, \Delta V}{P_u - P_\ell}$$

$$= 13.7 \times 4.44/(14.59-13.70)$$

$$= 68.3 \text{ m}^3.$$

If we further assume that some of the hydrogen filled the reactor vessel upper head (12 m^3 at 14 MPa, 450 K) and the rest the hot legs and the upper parts of the steam generators (56.3 m^3 at 14 MPa, 670 K), the total mass of hydrogen gas, M, is

$$M = \frac{AP}{R}\left(\frac{V_1}{T_1} + \frac{V_2}{T_2}\right) ,$$

where A is the molecular weight of hydrogen, P the pressure, R the universal gas constant, V the volume, and T the absolute temperature. The subscripts 1 and 2 denote the upper head, and the balance of the gas space in the primary system, respectively. So

$$M = \frac{(2 \times 10^{-3})\ (14 \times 10^{6})}{8.31} \times \left(\frac{12}{450} + \frac{56.3}{670}\right) = 373 \text{ kg.}$$

If the primary liquid (volume of 226 m^3, excluding the pressurizer liquid) was saturated with hydrogen at 14 MPa and 450 K, the total dissolved hydrogen is

$$M' = V\rho_{\ell}\xi P \quad ,$$

where V is the volume of the liquid, ρ_{ℓ} is the density of the liquid, ξ is the solubility ratio, and P is the pressure. Then

$$M' = 226 \text{ m}^3 \times 900 \text{ kg/m}^3 \times 2.776 \times 10^{-6} \times \frac{14}{0.1014} = 78 \text{ kg.}$$

The solubility ratio ξ (2.776×10^{-6} kg/kg-atm) is calculated from a correlation developed by Himmelblau.[11] The total hydrogen in the system is therefore 451 kg, almost exactly the same as the total production of 450 kg estimated in Ref. 5 (Volume 2, Part 2, p. 530), and slightly less than that estimated by Ref. 1 (472 kg, Appendix HYD, p. 10).

In the above calculation, the partial pressure of water vapor has been ignored. The vapor pressure in the upper head of the vessel would be negligible if the water temperature was at 450 K. Because the gas temperature in the steam generators and the hot legs was assumed to be 670 K, the vapor pressure cannot be determined without a heat transfer model to calculate the gas-liquid interface temperature. Any vapor pressure present would mean that the amount of hydrogen in the system was over-estimated. On the other hand, if the ERV flow rate was increased 20%, the amount of hydrogen calculated would have been increased by 20%. It may have been fortuitous that these two factors balanced out to yield the same amount of hydrogen estimated by others. If the calculated amount is correct, this would mean that the hydrogen produced during the accident had not been vented to the containment during the period when the block valve was undergoing rapid cycling.

6. CONCLUSION

Given the uncertainty in the TMI-2 electromatic relief valve design and the statistical fluctuations in the test data of similar valves, the prediction of the flow rates through the ERV during the accident would not be expected to have an accuracy better than 20%. In fact, the estimated flow rates out of the ERV given in Section 4 fell some 20% short of the supply to the primary system estimated from the decrease in inventory in the Borated Water Storage Tank. In calculating fission products carryover by the fluid flow through the ERV to the containment as a function of time, such an uncertainty should be borne in mind. It should also be noted that more than 80% of the liquid flow to the containment through the ERV occurred after 200 minutes, when most of the fission products may have already been released from the fuel to the primary coolant system.

From the simple analysis of pressure change when the block valve was being cycled, as presented in Section 5, the calculated amount of hydrogen (450 kg) in the primary system just prior to primary system depressurization (venting of hydrogen to the containment before the hydrogen burn in the containment) agrees surprisingly well with other independent estimates of hydrogen generation during the accident. The uncertainty, however, is difficult to quantify without a critical evaluation of the theory upon which the calculation was based. The final results of the examination of the extent of zircaloy oxidation in the core are needed to substantiate the calculation.

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