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Work performed under DOE Contract No. DE-AC07-76ID01570

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EGG-TMI-7482
January 1987

INFORMAL REPORT

STEAM GENERATOR SECONDARY SIDE EFFECTS UPON PRIMARY SIDE THERMAL-HYDRAULICS DURING THE TMI-2 ACCIDENT

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Published January 1987

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Prepared for the
U.S. Department of Energy
Idaho Operations Office
Under DOE Contract No. DE-AC07-76ID01570

ABSTRACT

During the Three Mile Island Unit #2 (TMI-2) accident, the primary to secondary heat transfer in the steam generators had a major impact upon the accident progression. The effects of steam generator heat transfer rates on the primary side thermal-hydraulics are presented and discussed for the first 300 minutes of the accident. Pertinent results from an analysis of tne primary system mass inventory are also presented.

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STEAM GENERATOR SECONDARY SIDE EFFECTS UPON PRIMARY SIDE THERMAL-HYDRAULICS DURING THE TMI-2 ACCIDENT

1. INTRODUCTION

During a small break loss of coolant accident, such as occurred at Three Mile Island Unit 2 (TMI-2) when the Pilot Operated Relief Valve (PORV) stuck open, the primary to secondary heat transfer in the steam generators has a major impact upon the accident progression. Increased heat transfer under conditions of two-phase flow can increase the condensation of steam, resulting in depressurization of the primary system. Alternately, heat transfer less than the energy generated in the core, can result in repressurization of the primary system, with a resulting increase in the mass loss through the break. The accident progression is governed by a mass and energy balance dominated by the transfer rates in the core, steam generators, and the small break. This progression can be complicated during certain accident segments by the effects of structural heat transfer, the presence of noncondensible fission product gases, oxidation of Zirconium which releases large amounts of energy and hydrogen, and the effect of noncondensible gases on the condensation potential in the steam generators.

In this report the effects of the steam generator heat transfer rates on the primary side thermal-hydraulics will be examined. Results of analyses using the previously calculated energy transfer rates based upon the secondary side conditions[1,2] will be presented and discussed.

Results from an analysis of the primary system mass inventory during the first 300 minutes of the TMI-2 accident will be presented. This analysis was performed to investigate the sensitivity of various portions of the accident to the make-up and letdown flow rates, and used the independent secondary analysis of primary to secondary heat transfer rates as one set of boundary conditions, and an analysis of the PORV critical flow rate based upon the pressurizer liquid level as another boundary condition. This analysis is documented in Reference 3.

2. CONDENSATION RATES

The primary to secondary heat transfer rates, obtained in Reference 1, can be used to calculate the rates of steam condensation in each of the primary loops. This is accomplished by using the measured primary system pressure in combination with the measured hot leg temperatures to obtain the steam enthalpy, and the measured cold leg temperatures to obtain the liquid enthalpy.[a] The calculated heat transfer rate divided by the change in enthalpy from the hot leg to the cold leg gives the steam condensation rate across each steam generator. These condensation rates are presented in Figures 1 and 2 for both steam generators during the first 300 minutes of the accident.[b] The condensation rates were high in both loops (on the order of 50-60 kg/s)[c] from 8 to about 25 minutes. After 25 minutes, indications are that the operators drastically decreased the Auxiliary Feedwater (AFW) injection rate,[d] which resulted in significantly decreased heat transfer rates. Although the A-loop Once Through Steam Generator (OTSG) remained a useful heat transfer mechanism during much of the accident, the B-loop OTSG was "isolated" by the operators during most of the accident. As a result, during the first 300 minutes, condensation in the B-loop was near zero for more than 160 minutes.

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a. By using the measured hot leg and cold let temperatures the effects of superheating and subcooling are accounted for.

b. Steam generator effects upon the primary thermal-hydraulics will only be presented for the first 300 minutes of the accident. The presented analysis was performed in support of the TMI-2 international standard problem, which is only to be performed for the first 300 minutes.

c. Based upon an AFW secondary injection rate of 30 kg/s per OTSG.

d. Documented in Reference 1.

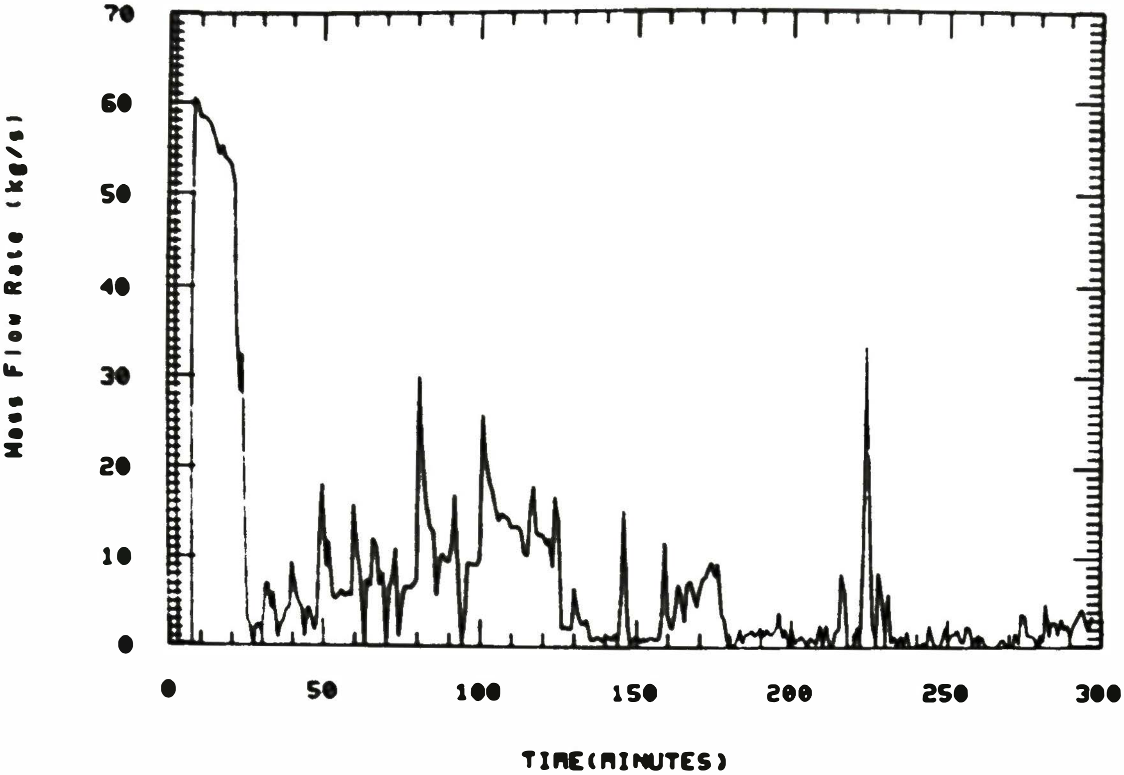

Figure 1. A-loop OTSG primary side condensation rate due to OTSG heat transfer.

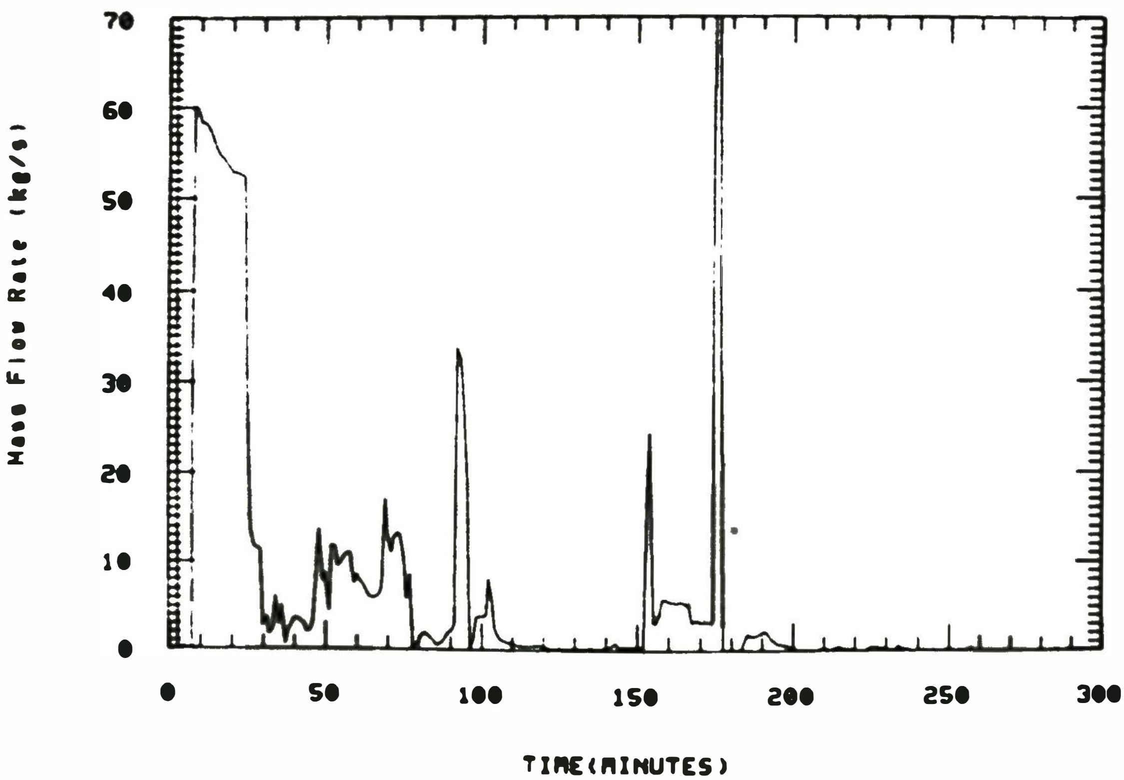

Figure 2. B-loop OTSG primary side condensation rate due to OTSG heat transfer.

3. THERMAL-HYDRAULIC ANALYSIS

The TMI-2 accident initiating event was a trip of the main feedwater pumps, which in turn resulted in a trip of the turbines. The PORV automatically opened a few seconds later, on increasing system pressure, and the reactor scrammed on high pressure about 8 seconds after the feedwater pump trip. Following scram the system depressurized, and the PORV should have closed. However, the PORV was stuck open, which the operators failed to recognize until 139 minutes into the accident, at which time the PORV block valve was closed. In addition, the block valves in the AFW injection lines were initially closed, preventing auxiliary injection into the OTSG secondaries until 8 minutes into the accident when this condition was discovered. Because of the blocked AFW lines, the steam generators secondaries boiled dry in 1 1/2 minutes.[a] When the AFW injection was established, heat transfer from the primary into the secondaries increased dramatically. The primary system temperatures, which had been rapidly increasing, immediately began decreasing, finally reaching the A-loop secondary side saturation temperature by 23 minutes. This is about the same time that secondary levels began to be reestablished.[b] From this time, until the B-loop pumps were shutdown at 73 minutes, the primary temperatures followed the secondary saturation temperatures. This is shown in Figures 3 and 4 in which the primary saturation temperature is compared to the primary cold leg temperature and the secondary saturation temperature in each loop.

At 73 minutes, when the B-loop pumps were shutdown, the B-loop heat transfer rate rapidly decreased. Prior to the pump trip the condensation rate in the B-loop OTSG was about 13 kg/s (see Figure 2). This rate decreased to near zero by 78 minutes,[c] and remained between

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a. This condition was evident from the falling secondary pressures.

b. The A-loop OTSG secondary was dry until 20 minutes, when the level began increasing. The B-loop OTSG secondary was dry until 23 minutes, when the level began increasing.

c. At 77 minutes the B-loop secondary level began a sustained decrease, indicating that AFW injection had been terminated into the B-loop OTSG.

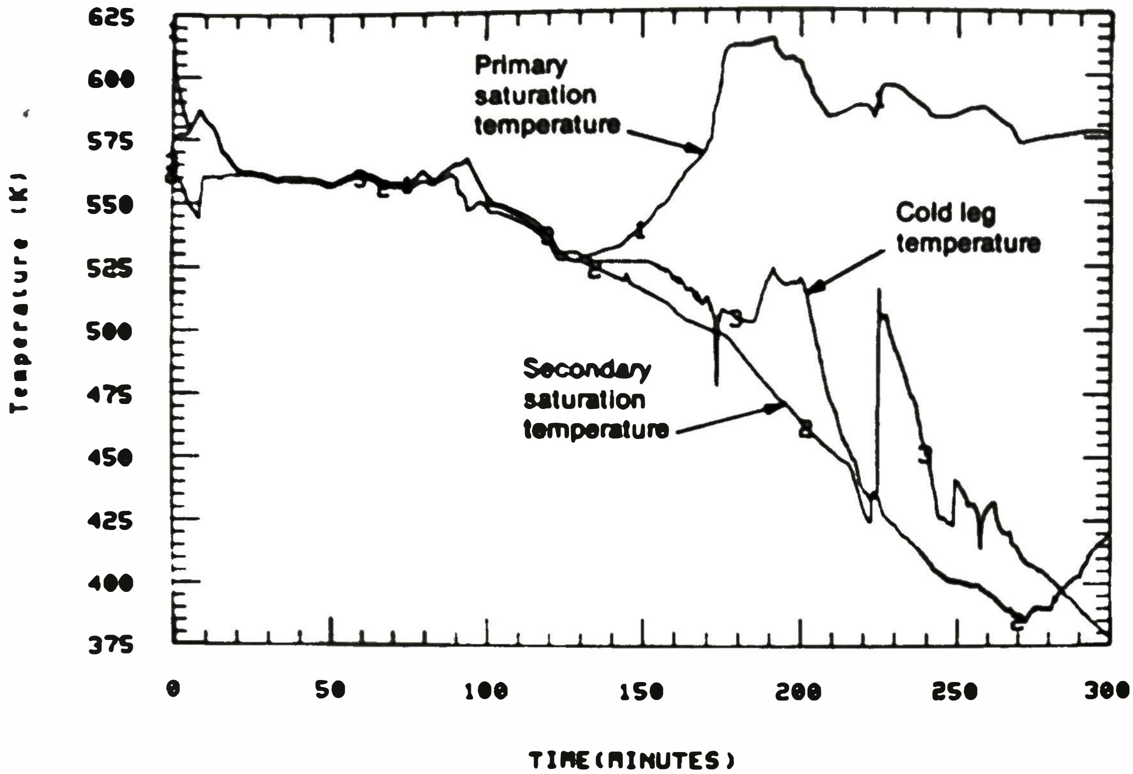

Figure 3. Comparison of primary saturation with A-loop secondary saturation and cold leg temperatures.

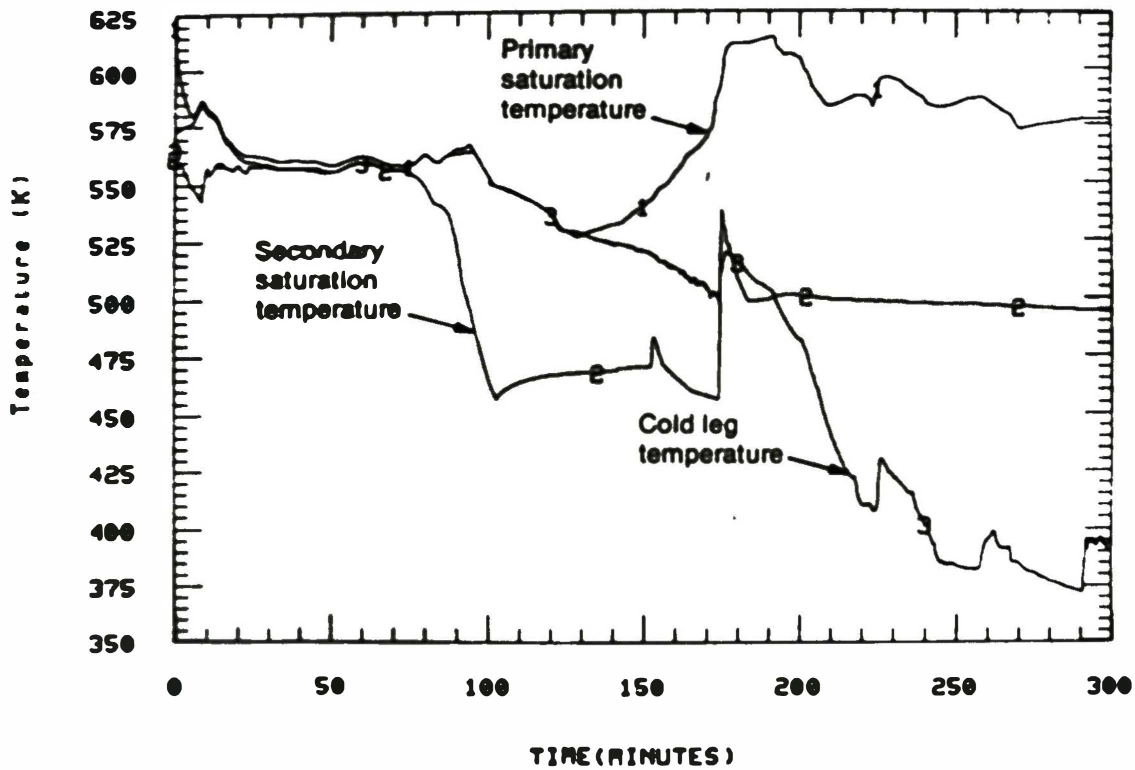

Figure 4. Comparison of primary saturation with B-loop secondary saturation and cold leg temperatures.

0.5-3 kg/s until 92 minutes. At about 85 minutes AFW injection into the A-loop OTSG was apparently terminated.[a] By 92 minutes the A-loop OTSG secondary had again boiled dry. The operators apparently noticed this and attempted to reestablish AFW injection into the A-loop OTSG. However, they apparently opened the wrong AFW injection valve (EF-V11B), because the B-loop secondary level rapidly increased for about 3 minutes, and then continued to decrease until 102 minutes, at which time the operators isolated the B-loop OTSG. When the AFW injection into the A-loop OTSG was terminated at 85 minutes, the primary side saturation temperature and the cold leg temperatures began increasing, no longer following the secondary saturation temperature. This is clearly shown in Figure 3. When the AFW injection was reestablished into A-loop OTSG at 95 minutes, the primary temperatures rapidly decreased until again reaching secondary saturation temperatures at 100 minutes.

At 100 minutes the A-loop pumps were shutdown. This terminated the initial forced convection cooling portion of the accident. At 102 minutes the B-loop OTSG was isolated by closing the B-loop turbine bypass valve (MS-V15B) on the steam side, and closing the AFW injection control valve (EF-V11B) on the liquid injection side.[b] Even though the B-loop OTSG was isolated, sufficient energy was being removed through the open PORV and the A-loop OTSG (which was being filled to approximately the 50% level on the operating range) to continue depressurizing the primary system. This depressurization closely followed the A-loop OTSG secondary pressure, and continued until 128 minutes, at which time the primary began to repressurize. (The repressurization continued through the system transient resulting from the restart of the 2B reactor coolant pump at 174 minutes).

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a. This is based upon the analysis presented in Reference 1, and the falling secondary level.

b. Note that the B-loop OTSG secondary level continued a very slow increase, which led the operators to suspect a primary to secondary leak. A more likely explanation was a leaking control valve in the AFW line. As a result, the steam generator was not completely isolated and a small amount of heat transfer continued to occur.

At 112 minutes the A-loop hot leg temperature began a rapid increase, above saturation temperature (shown in Figure 5). At 123 minutes the B-loop hot leg temperature began rapidly increasing. The superheated steam was most certainly generated due to core uncovery, and the difference in response times of the two hot leg temperatures to the core uncovery can be explained in terms of steam transport times from the core to the hot leg Resistance Thermal Device (RTD) located at an elevation 13 m above the core. At 112 minutes the A-loop OTSG was condensing about 13 kg/s of steam. This would correspond to a transport time of about 0.4 minutes (22 seconds). On the other hand, the nearly isolated B-loop OTSG was only condensing about 0.4 kg/s, corresponding to a transport time of 12 minutes.[a] This is very near the observed difference in temperature responses of 11 minutes.

By 125 minutes the level in the A-loop OTSG had reached 50% on the operating range (630 cm), and the operators terminated AFW injection.[b] During the next 35 minutes AFW injection was resumed and terminated twice in an attempt to maintain a level near 50%. The AFW injection, coupled with continued steaming through the A-loop Atmospheric Dump Valve (ADV) (MS-V3A), resulted in a continued depressurization of the A-loop OTSG secondary. However, at 128 minutes the primary system started to repressurize. This was an abrupt change in slope from the primary depressurization occurring prior to this time, in which the system pressure had been closely following the A-loop OTSG secondary pressure. The primary condensation rate calculated from the secondary conditions dropped from a rate of 10-18 kg/s prior to 125 minutes, to values on the order of 1-2 kg/s following termination of the AFW injection. When the AFW injection was resumed at 129 and 145 minutes, the condensation rate briefly increased to 2-6 kg/s. Since steam generation in the core was about 14 kg/s (based upon

a. Transport times are based upon a system pressure of 5.6 MPa, a hot leg flow area of 0.657 m^2, and a distance of 15 m from the core to the hot leg temperature measurement.

b. This is an assumption documented in Reference 1, based upon a sharp decrease in level after the fill. The primary side level was about 720 cm relative to the bottom tube sheet at 125 minutes, based upon the mass balance analysis in Reference 3. This level had decreased down to about 250 cm by 160 minutes.

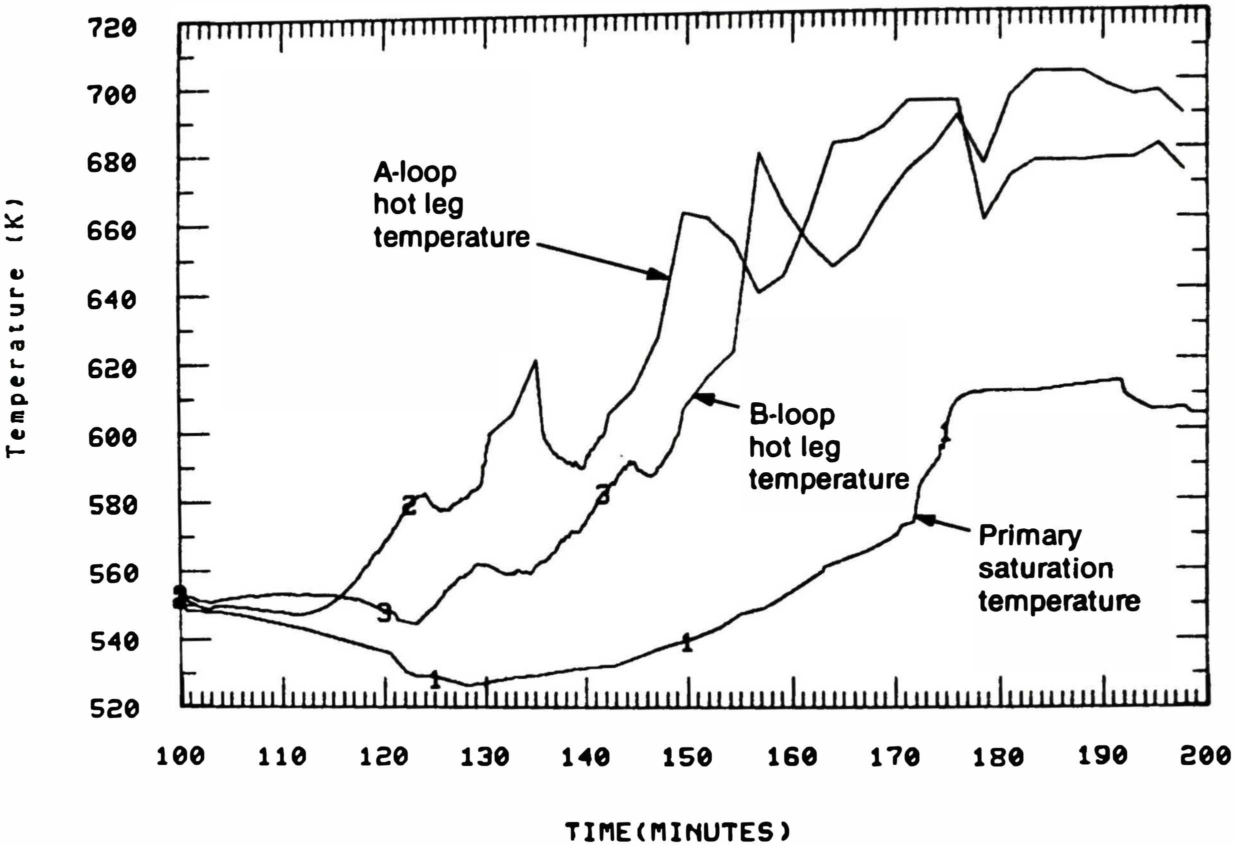

Figure 5. Comparison of primary saturation temperature with the measured hot leg temperatures.

decay energy), and the flow through the PORV was about 5 kg/s (based upon analysis of the pressurizer critical flow), it is obvious that more steam was being generated than was escaping or being condensed, which would account for the system repressurization.[a] At 134 minutes the A-loop cold leg temperature ceased to follow the A-loop OTSG secondary saturation temperature. Instead, the cold leg temperature remained constant until after 150 minutes. This is further evidence of the drastically reduced primary to secondary heat transfer in the A-loop.

The mechanisms involved, and their relative magnitudes, resulting in the drastically decreased heat transfer into the A-loop OTSG are not intuitively obvious. The major heat transfer mechanism was probably the AFW spray onto the tops of the exposed tubes. With the primary side of the tubes filled with a mixture of steam and noncondensible gases, heat transfer was probably large. When the AFW injection was terminated this heat transfer mechanism would stop. However, as soon as the AFW injection was terminated the primary side level would have begun to decrease due to the continued letdown flow of about 6-8 kg/s[b] (the large condensation rate prior to this time was probably maintaining the A-loop cold leg liquid filled up to the bottom of the pump discharge). Within a few minutes the primary side level would have dropped below the secondary level. With the secondary side increasingly subcooled relative to the primary side some condensation should have continued, with the cold leg temperature following the secondary saturation temperature.[c] Since this did not occur, some

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a. Steam generation in the core at this time is estimated from the ANS core decay energy curve, which has an uncertainty of about ±5%. In addition, core uncovery had began to occur and not all of the decay energy would have been going into steam generation. Steam generation in the core was probably less than the stated value of 14 kg/s; however, it is this authors engineering judgment that the conclusions reached are still valid. Uncertainty in the steam flow rate out the PORV is probably less than ±0.5 kg/s.

b. Based upon an analysis of the letdown cooler outlet temperatures.

c. It is possible that all flow was away from the cold leg RTD measurement in the pump suction, effectively isolating this temperature measurement from the steam generator.

other mechanisms must have been involved. One possible explanation involves the decreased condensation potential resulting from noncondensible gases being released from the core and blanketing the condensation surfaces. It is possible that fuel rod rupture had began occurring prior to 134 minutes,[a] releasing helium and the fission product noble gases Krypton and Xenon from the fuel rod gap,[b] and that these noncondensible gases blanketed the heat transfer surfaces in the A-loop OTSG, thus significantly decreasing the condensation potential. Another possible explanation is that the Zirconium rod cladding had begun to oxidize, releasing hydrogen into the system. However, it is generally believed that rod rupture would occur prior to the initiation of the Zirconium oxidation, and that hydrogen production did start until about 160 minutes.

At 153 minutes the operators increased the B-loop OTSG secondary level from about 250 cm to about 650 cm by 174 minutes. This action significantly increased the heat transfer rates into the B-loop OTSG (primary side condensation rates increased from about 0.3 kg/s to around 5 kg/s). The increased heat transfer can be explained in terms of the AFW injection being sprayed directly onto the steam generator tubes near the top of the OTSG. Heat transfer prior to this time probably occurred near the top of the liquid surface (AFW injection was limited to a leakage of about 0.1 kg/s which would have been insufficient to spray onto the tubes). The primary side steam flow down to the condensation surface may have tended to carry the noncondensible gases down to this level, resulting in a higher steam partial pressure near the top of the steam generator primary side. Thus, the AFW injection could have had a more significant effect on the heat transfer than was occurring in the A-loop. The AFW injection resulted in a 0.4 MPa increase in the secondary pressure,

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a. Superheated temperature was first measured in the A-loop hot leg at about 112 minutes, indicating core uncovery had occurred by that time. At 134 minutes the first indication of radiation release into containment occurred when a reactor building air sample monitor particulate channel radiation reading began increasing and eventually went off scale high.

b. It is estimated that 1% of the total core inventory of the fission product gases were contained as free gases in the fuel gap. It is further estimated that the initial inventory of Kr was 3.62 kg, and Xe was 42.2 kg.

although 3 minutes later the secondary pressure was back down to the initial pressure, and continued a slow depressurization until 174 minutes.

Following shutdown of the B-loop pumps at 73 minutes, the B-loop water level would have been up to the level of the bottom of the pump discharge piping. Continued condensation in the B-loop OTSG would have tended to maintain the B-loop water level at this elevation,[a] which corresponds to a secondary level of 715 cm.

At 171.3 minutes the operators attempted to restart the 2A pump.[b] This attempt was unsuccessful. However, at 173.1 minutes the A-loop cold leg temperature responded to the attempted 2A pump restart with an abrupt 28 K drop[c] (to below the A-loop OTSG saturation temperature by some 15 K), and then recovered back to the initial temperature by 174.4 minutes. It is possible that this temperature drop was a result of the cold pump seal injection water leaking through the pump seals, when the pump was not running, and falling down on the exposed RTD (the A-loop cold leg was nearly empty at this time[d]).

At 174 minutes the 2B main reactor coolant pump was restarted and ran until 193 minutes. With a B-loop water level up to the pump casing prior to the pump restart,[e] some 30,000 kg of liquid was available for injection into the vessel. It is likely that a significant portion of this liquid bypassed the core and was injected into the A-loop through the

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a. Based upon the mass balance analysis results (see Reference 3).

b. The timing of this event is based upon the times recorded on the alarm printer for the RCP 2A Oil Lift Pump Discharge Pressure reaching a normal value. This pressure was recorded to alarm low at 173.3 min.

c. Uncertainties in the cold leg temperatures recorded on the reactimeter system have been estimated at ±1.1 K.

d. Based upon the mass balance calculations, which estimate the A-loop level at 0.2 m above the elevation of the core bottom.

e. This level estimate is based upon the results of the system mass balance calculations.

A-loop pump discharges,[a] raising the A-loop water level in the cold legs. Large amounts of the liquid injected into the core were vaporized on the hot exposed core,[b] resulting in a rapid primary system pressure increase of 5.5 MPa within 2 minutes. The increased forced convective flow through the B-loop dramatically increased the B-loop OTSG heat transfer rates (primary condensation increased from 3 kg/s to over 160 kg/s before dropping to zero at 177 minutes). This was coincident with a steaming from the B-loop OTSG initiated by the operators at 175 minutes.[c] The 2B pump transient resulted in a 4.0 MPa secondary pressure increase by 175 minutes, which was terminated by the steaming from the B-loop OTSG. Steaming was continued until 183.7 minutes when the operators attempted to isolate the B-loop steam generator a second time by closing the turbine bypass control valve (MS-V15B) and the AFW injection valves (EF-V11B, EF-V12B, and EF-V5B).[d] Following this action the secondary level continued to slowly increase, which the operators interpreted as a primary to secondary leak in one of the steam generator tubes. A more likely explanation is a leaking AFW injection valve. However, following the attempted isolation, the heat

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a. Blockage of the core due to fuel liquefaction has been estimated to exceed 75% of the core flow area, based upon the core end state conditions. It is difficult to calculate the actual core bypass at 174 minutes due to the rapid vaporization which occurred. However, an assumed bypass of 15,000 kg in the mass balance calculations, Reference 3, resulted in a mass distribution following the 2B pump transient which predicts a secondary core uncovery at 193 minutes, as appears to have occurred based upon the core exit thermocouple (TC) alarms which occurred at this time.

b. An estimated 5,000 kg of steam were generated between 173-176 minutes.

c. The operators opened the B-loop MSIVs for 12 seconds at 176.1 minutes. However, this action had no affect upon the secondary side conditions, since the turbine stop valves are downstream of the MSIVs (in the steam chest) and had closed upon trip of the turbine. In addition, the turbine bypass valves and the ADVs used for steaming from the steam generators during the accident are upstream of the MSIVs. It is apparent from the secondary pressure that steaming from the B-loop OTSG was initiated at 175 minutes, and continued until 183.7 minutes.

d. Timing for these actions are verified on the alarm printer for the closure of the turbine bypass valve. This is also apparent from the secondary pressure response.

transfer into the B-loop OTSG was negligible during the remainder of the first 300 minutes of the accident (primary side condensation rates varied from 0 to 0.5 kg/s).

The 2B pump restart resulted in a jump in the B-loop cold leg temperature of 22 K, which then began decreasing. By 193 minutes, when the 2B pump was stopped, the cold leg temperature had decreased down to the secondary saturation temperature. This temperature continued to decrease until 225 minutes. The decrease after 200 minutes can perhaps be explained in terms of cold HPI from 200 to 217 minutes. However, there is no obvious explanation for the decrease in B-loop cold leg temperature from 193 to 200 minutes.[a] There is no evidence that the RTD had failed, therefore an external source of cold liquid is required to explain the temperature response. One possibility is that the pump seal injection was still on and leaking into the system with the pumps off. This could result in cold liquid in the vicinity of the cold leg RTD temperature measurement (located in the pump suction).

At 225 minutes the cold leg temperatures in both loops abruptly jumped (the A-loop temperature increased by 86 K in less than 1 minute, whereas the B-loop temperature increased by only 23 K in the same time period). This event has been attributed to the relocation of molten core material into the vessel lower plenum, which probably resulted in reverse flow up the downcomer and through the pump discharges. The primary system pressure increased by 2.8 MPa, indicating the generation of large amounts of steam, which would have displaced the liquid in the vessel and provided the driving force for the reverse flow. Simultaneous with the cold leg temperature responses, the secondary pressure (and thus saturation temperature) in the A-loop steam generator also jumped. This was an apparent response to the reverse flow of hot liquid on the primary side

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a. Note that make-up and HPI enter the primary system in the horizontal cold leg segment prior to entering the downcomer. Thus, for the make-up/HPI liquid to get to the RTD in the pump suction, the level in the downcomer and pump discharge piping must increase up to the bottom of the pump discharge.

into the steam generator, resulting in increased primary to secondary heat transfer. The B-loop OTSG showed no response to the 225 minute event. However, the B-loop cold leg temperature was recorded as being very subcooled relative to the B-loop OTSG secondary saturation temperature (approximately 90 K subcooled). In addition, following the restart of the 2B pump, the B-loop cold legs would have been mostly voided. This may have affected the amount of reverse flow into the B-loop cold legs, although it would be expected that this would result in more flow into the B-loop rather than less flow. From the very different cold leg temperature responses in the A and B-loops, it is obvious that an asymmetry in the amount of reverse flow existed. One possible explanation is an asymmetry in the molten core flow (indications are that molten material flowed down the southeast side of the core, which is on the B-loop side of the vessel).

Following the 225 minute event, the A-loop cold leg temperature began decreasing, dropping 94 K in the next 23 minutes. At 248 minutes the operators started the 2A main reactor coolant pump, which ran for about 1 minute. The primary system pressure responded with a slow repressurization, whereas the A-loop cold leg temperature responded with a sharp increase of 20 K. There was no apparent response of either steam generator secondary to this event.

The A-loop steam generator secondary pressure had been steadily decreasing since the primary system began to repressurize at 128 minutes (with the exception of the event at 225 minutes), as a result of continued steaming from the OTSG. This secondary depressurization continued until 272 minutes when the secondary pressure reached atmospheric pressure; at which time the A-loop OTSG secondary pressure began increasing. By 285 minutes the secondary saturation temperature increased above the measured A-loop cold leg temperature. The 272 minutes secondary repressurization was coincident with the resumption of AFW injection into the A-loop OTSG[a] at a low rate of about 1 kg/s. The secondary level was at about 600 cm. It is possible that the operators had manually shut the

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a. AFW injection into the A-loop OTSG had been terminated at about 233 minutes based upon the secondary level analysis presented in Reference 1.

turbine bypass valve, resulting in the repressurization when coupled with the small AFW injection. However, no such action was recorded on the alarm printer. Bottling up the secondary side could result in an increased secondary pressure without resulting in a response from the cold leg RTD, if there was no flow from the steam generator to the RTD. This is a likely condition to have existed, since HPI was on and cold liquid was probably flowing from the HPI injection location in the pump discharge back through the pumps (liquid level in the primary was probably up into the hot leg.[3]

At about the same time as the secondary repressurization began, the primary system depressurization stopped and the primary began to repressurize. The HPI had been initiated at 267 minutes, which may have been the cause of the primary repressurization. Large amounts of noncondensible gases would have been present in the primary system. Compression of these gases by the HPI liquid could have been the repressurization mechanism.

4. CONCLUSIONS

The primary to secondary heat transfer rates, derived from the secondary level analysis, have been coupled with primary side conditions to estimate the primary side steam condensation rates during the first 300 minutes of the TMI-2 accident. Knowledge of these rates, in addition to steam generation rates in the core and mass flow rates out of the PORV, permits explanation of the interaction of the primary thermal-hydraulics with the secondary side conditions. These interactions have been examined for various portions of the accident and analyses presented.

The steam generators had a major impact upon the primary system depressurization until release of noncondensible gases into the primary, which probably occurred prior to 134 minutes. Simultaneous with this release the steam generators heat transfer rates were drastically reduced[a] which effectively decoupled the steam generators from the primary system. An exception to this occurred on the restart of the 2B reactor coolant pump. However, the increased heat transfer rates resulting from the pump restart only lasted for a few minutes. Accurate prediction of the primary side thermal-hydraulics during the TMI-2 accident requires accurate modeling of the heat transfer to the steam generators during the first 300 minutes of the accident.

a. Note that the major part of this decrease was due to termination of AFW injection into the A-loop OTSG.

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