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EFFECTS OF LATERAL SEPARATION OF OXIDIC AND METALLIC CORE DEBRIS ON THE BWR MK I CONTAINMENT DRYWELL FLOOR*

C. R. Hyman, C. F. Weber, S. A. Hodge
Oak Ridge National Laboratory
Oak Ridge, Tennessee

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EFFECTS OF LATERAL SEPARATION OF OXIDIC AND METALLIC CORE DEBRIS ON THE BWR MK I CONTAINMENT DRYWELL FLOOR

C. R. Hyman*   C. F. Weber*
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ABSTRACT

In evaluating core debris/concrete interactions for a BWR MK I containment design, it is common practice to assume that at reactor vessel breach, the core debris is homogeneous and of low viscosity, so that it flows through the pedestal doorway and spreads in a radially uniform fashion throughout the drywell floor. In a recent study performed by the NRC-sponsored Severe Accident Sequence Analysis (SASA) program at Oak Ridge National Laboratory, calculations indicate that at reactor vessel bottom head failure, the debris temperature is such that the debris metals (Zr, Fe, Ni, Cr) are completely molten while the oxides (UO_2 ZrO_2, FeO) are completely frozen. Thus, the frozen oxides are expected to remain within the reactor pedestal while the molten metals radially separate from the frozen oxides, flow through the reactor pedestal doorway, and spread over the annular region of the drywell floor between the pedestal and the containment shell.

This paper assesses the impact on calculated containment response and the production and release of fission product-laden aerosols for two different cases of debris distribution: uniform distribution and the laterally separated case of 95% oxides-5% metals inside the pedestal and 5% oxides-95% metals outside the pedestal. The computer codes used are CORCON-MOD2, MARCON 2.1B and VANESA.

INTRODUCTION

This paper reports the results of a study recently completed by the Severe Accident Sequence Analysis (SASA) Program[†] at Oak Ridge National Laboratory to

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*Oak Ridge National Laboratory

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investigate the effects of a postulated lateral separation of metallic and oxidic core debris on the drywell floor of a BWR MK I power plant. The impetus for such a study arises out of SASA estimates of the initial conditions of the core debris as it leaves the failed reactor vessel, and the desire to know (in a bounding sense) the containment loading and aerosol generation consequences of corium/concrete interactions for various assumed distributions of corium on the drywell floor. The reference BWR 4 MK I plant used for the study is Unit 1 of the Tennessee Valley Authority (TVA) Browns Ferry plant, and the transient studied is the corium/concrete interaction phase of a hypothetical Station Blackout accident.

Because the initial conditions and timing of corium/concrete interactions depend primarily on the preceding invessel phase of the transient, ORNL SASA program degraded core methodology follows the expected sequence of events from the point where the core is uncovered, through core heatup, core degradation, material relocation to the vessel lower head, vessel lower head failure, and core debris/concrete interactions on the drywell floor. While the debris is in the bottom head of the reactor vessel, water boiloff quenches the debris to 1630 K, at which point the water inventory is depleted and debris heatup resumes. It is postulated that one or more of the stainless steel bottom head penetrations would fail by melting when the debris reaches 1811 K and that the hot vessel gases would blow through and around the debris bed and out the failed penetration (without ejecting the frozen debris), thus depressurizing the primary system. At a debris temperature of 2200 K, all of the debris is assumed to be sufficiently fluidized to run out the failed penetrations, where it is instantaneously deposited onto the drywell floor. A portion fills the drywell sumps, whereby vaporization of sump water (3175 kg) produces sufficient Zr-steam reaction to raise the debris temperature to 2280 K. At sump dryout, the core debris/concrete interaction is assumed to begin.

At 2280 K, the core debris exists as a solid-liquid mixture. The metallic components of the debris (Fe, Zr, Cr, Ni) are completely molten and in a pure state have a viscosity comparable to that of water at room temperature. The oxide debris (UO_2, ZrO_2, FeO), on the other hand, is completely frozen. Accordingly, it is possible that a large portion of the liquid metals would separate from the oxides, flow through the pedestal doorway, and spread over the annular region of the drywell floor between the outer wall of the pedestal and the drywell shell. This presents a very different situation from what is commonly assumed in BWR severe accident analysis — that the debris mixture is homogeneous and of low viscosity, so that uniform radial dispersal on the drywell floor would occur.

The two debris distributions investigated in this study are uniform radial spreading and a laterally separated debris distribution in which bounding estimates of 95% oxide debris mass with 5% metallic debris mass are assumed inside the pedestal with the remaining 5% oxide debris and 95% metallic debris outside the pedestal.

METHODOLOGY AND MODELING ISSUES

The methodology used to conduct this study is described in detail in Reference 1. The sequence of calculations begins by making a single MARCON 2.1B* calculation for the uniformly distributed core debris. The primary containment response for this calculation is then used as an initial estimate of the thermal hydraulic boundary conditions required to execute a stand-alone CORCON-MOD2 (3) calculation for the expedestal region of the laterally separated distribution. Because another MARCON execution is required for the calculation of the inpedestal region of the laterally separated case, some iteration is required in order to establish convergence of the primary containment response to the simultaneous inpedestal and expedestal corium/concrete interactions.

Two modeling issues arose while performing this study. First, it has been observed that as much as 100% variation in cumulative gas release can result by using various reasonable combinations of noding and timestep size. A parameter study, performed to address CORCON sensitivity to these parameters and to determine optimum values while maintaining reasonable computation costs, is described in Appendix A of Reference 1. Timestep/noding combinations of 20 s/11 cm, 7.5 s/7 cm, and 15 s/7 cm were selected for the uniform, inpedestal, and expedestal calculations, respectively. The second issue is the effect of drywell sump modeling on calculated results. It was found, for the uniformly spread debris case, that although neglect of the sumps decreases the effective overall debris/concrete interfacial area by only 5%, the rate of oxidation is slowed such that depletion of the Zr inventory occurs about two hours later than when the sumps are modeled. The cause of this has been traced to the crusting model employed by CORCON, which may not be adequate for the sump geometry. Additional information is provided in Appendix B of Reference 1.

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*MARCON 2.1B provides a dynamic calculation of the effect of corium/concrete interactions on containment response. It is based upon the MARCH 2.0 (2) Code with CORCON-MOD2 instead of the original INTER algorithm and also includes extensive modifications to incorporate all ORNL developed BWR models.

DISCUSSION OF THERMAL HYDRAULIC RESULTS

Comparisons of the debris layer temperatures for the uniformly spread and the laterally separated case are shown in Figs. 1 and 2. In these calculations, based upon Station Blackout for Browns Ferry, the debris leaves the reactor vessel at time 807 min and is comprised of 202,601 kg of oxides and 92,170 kg of metals. The calculation is carried out for 693 min, to an accident time of 1500 min. For the first hour, the inpedestal oxide layer temperature (Fig. 1) is somewhat higher than that for the uniform distribution. This is because of a higher concentration of decay heat in the inpedestal region of the separated case compared to the inpedestal region of the uniformly spread distribution.

On the other hand, the metal layer temperature (Fig. 2) for the expedestal debris is substantially less than that calculated for the uniformly spread case. This is because the expedestal debris has only about 14% of the total debris decay heat (the rest being inpedestal); thus, once the chemical energy source of Zr oxidation is extinguished, the expedestal metals have little energy source available to compensate for heat losses to the drywell atmosphere. In the uniform case, the metals are always coupled to the oxides via interlayer heat transfer and have an elevated temperature throughout the calculation.

Effects of lateral separation of core debris upon cumulative gas release are significant (Table 1). In the uniform case, 89 mole % of the release is combustible (H_2 and CO) whereas in the laterally separated case, the sum of the combustible release from the inpedestal and expedestal regions amounts to only 58 mole % of the total. The cumulative combustible release (for 693 min of transient after reactor bottom head failure) of 849 kg-moles for the uniformly distributed debris may be compared with only 683 kg-moles for the separated case — a difference of ~24%. On the other hand, noncombustible gas release for the uniformly spread debris is only 95 kg-moles, about 19% of the 491 kg-moles of noncombustibles released in the laterally separated case. The total gas releases are 944 kg-moles and 1174 kg-moles for the uniform and separated cases respectively. Thus, total release is about 24% greater for the laterally separated case.

The difference in the gas release behavior of the two cases is explained by the location of the metals and the metal chemistry involved. For the uniform case, 100% of the oxides and metals are considered and for most of the calculation, the metals lie beneath the oxides. Because of the large metal inventory, the metal layer overflows the sumps and forms a layer on the drywell floor both inside and outside the reactor pedestal. Fission product decay heats the oxide layer which in turn heats the metal layer so that elevated layer temperatures and concrete ablation are calculated throughout the transient. Because ablation is predominantly along the drywell floor, most of the ablation gases (CO_2 and H_2O) sparge through the metal layer where they are converted into CO and H_2. Consequently, little noncombustible gas release is calculated for the uniform case.

For the expedestal area of the laterally separated case, the gas release composition is similar to that discussed for the uniform case. Concrete ablation is again primarily along the drywell floor whereby most of the ablation-produced CO_2 and H_2O flow into the metal layer and are converted to CO and H_2. However, because the predominantly metallic debris in this region of the drywell floor possesses little fission product decay heat (14% of the total), concrete ablation rapidly decreases as the exothermic Zr oxidation reactions deplete the Zr inventory. As a result, less CO_2 and H_2O are created and passed into the metal layer; therefore, smaller quantities of CO and H_2 are released compared to the uniform case.

The inpedestal area of the laterally separated case exhibits a different scenario of gas release than either the expedestal area or the uniformly distributed case. For the inpedestal debris, only a small fraction of the metals is considered (5% by mass), and for most of the calculation, CORCON places these metals in the bottom of the sump. Oxidic debris overlies the metallic, fills the remainder of the sump, and forms a thick layer on the drywell floor inside the pedestal. Because 86% of the total fission product decay heat but only 67% of the total debris mass is included in this inpedestal calculation, the oxide layer temperature and the concrete ablation rate remain elevated throughout the transient. However, since most ablation occurs due to concrete attack by the oxide layer, which overlies the metal layer, the evolved CO_2 and H_2O bypass the metal layer and directly enter the drywell atmosphere. Some combustible gas is also released as the metallic debris in the bottom of the sump continues to ablate concrete; these ablation gases react with the metals to produce CO and H_2. Thus, for the inpedestal area of the laterally separated case, the released gases are a mixture of both combustible and noncombustible gases with the majority being noncombustible.

DISCUSSION OF AEROSOL AND FISSION PRODUCT RELEASE

A major importance of the core-concrete reaction is its effect on the release and transport of fission products from the core debris. To analyze this phenomenon, the VANESA (4) code was run for each CORCON calculation described above (uniform distribution; metal-rich expedestal debris, oxide-rich inpedestal debris). Each VANESA result describes the transient aerosol and fission product behavior resulting from the particular pattern of temperatures, reactions, and gas flows in the debris configuration being studied.

Initial debris inventories for the uniform and separated corium cases are identical, since both result from the same accident sequence events prior to vessel failure. Nuclide inventories for most elements were obtained using the retention factors calculated by the MARCON code; those for important volatile elements (I-Br, Cs-Rb, Te-Se, and Xe-Kr) were obtained from the ORNL code TRENUS. Table 2 lists the actual values for initial inventories used. The second column represents the total corium inventory for both uniform and separated cases. Columns 3 and 4 depict the division of separated corium into inpedestal and expedestal regions. Oxide elements are partitioned so that 95% are inside the pedestal whereas only 5% of the metallic elements are located there. The remainders are located outside the pedestal. It should be noted that the VANESA code does not treat all elements individually, but groups certain ones together and treats them as the characteristic element shown in italics in the table.

Several VANESA results for the uniform case are compared with those for the separated case in Figs. 3–5. Since the latter required two runs (inpedestal and expedestal), it was necessary to add the calculated values for each data point to obtain a single value representing the separated corium case. In comparing VANESA results with CORCON output, it should be noted that VANESA always assumes an oxide layer overlying a metal layer. Thus the CORCON layer flip will impact VANESA calculations only through secondary effects such as temperatures and gas flows.

Total aerosol releases for the two cases are shown in Fig. 3. Both exhibit an early peak, which diminishes considerably after the first hour. This behavior follows the oxide temperature (Fig. 1) and total gas flow (Fig. 4). Except for a slower descent from the peak, the uniform case is lower during most of the transient. This corresponds closely to the slightly higher oxide temperatures and gas flows occurring in the separated case. The sharp drop late in the transient is due to a reduction in the vaporization of CaO, which forms the primary aerosol component (over 95% in both cases) during the middle portion of the sequence.

The releases of several important fission products are shown in Fig. 5. Of note is the pattern for the oxidic elements CsI, BaO, and SrO, where the separated case produces a quicker, but lower overall, release than the uniform case. In both cases, the large initial releases correspond to the high temperatures occurring early, with only slight releases after temperatures drop below 1900K. The differences in timing and magnitude for the two cases are explained by noting that the gas release rate in the separated cases falls off dramatically at 900 min, while it peaks after this time in the uniform case.

This gas release behavior is due to the oxidation of the accumulated inventory of metal layer carbon (produced by the CORCON coking reaction of Zr with CO_2) subsequent to the depletion of Zr. Consideration of the reactions involved shows that the influx of gas into the metal layer is effectively doubled (volumetrically) so that a sharp pulse of gas is released as this carbon is oxidized.

Because the uniform case maintains a high concrete ablation rate after Zr depletion, the inflow of CO_2 and H_2O into the metal layer of the uniform case is higher than that of the separated case. thus, even though the accumulated carbon inventory is about the same in both cases, the uniform case has more CO_2 and H_2O with which the carbon can react. Therefore, the gas release peak for the uniform case is larger than that of the separated case. This gas pulse (at elevated temperature) rapidly releases volatile fission products; hence, the fission product release from the oxidic debris is higher for the uniform case.

In a general sense, this explanation is also consistent with Table 1, where it is seen that the uniform debris cumulative gas release is higher than that of the inpedestal region of the separated debris. Since the inpedestal region of the separated case is the location of most of the oxidic fission products, it is expected that less gas flow releases fewer fission products.

The release of metal layer fission products is explained by remembering that most of these fission products are found in the expedestal region of the separated case. From Fig. 1 it is seen that the metal layer temperature is higher for the expedestal region than the uniform case for the time period 800-860 min. This accounts for the more rapid initial release of Te for the separated case. After 860 min, the metal layer in the uniform case begins to heat up (Fig. 1) due to melting of the oxide layer below, and coupled with the gas pulse described earlier, the uniform case Te release accelerates so that Te inventory rapidly approaches the 70% level.

Molybdenum is the reverse of Te, showing no release in the uniform case, and a slow but steady release in the separated case. The release is small (<4%) and occurs in the small inventory of metals in the inpedestal region of the separated case. After 1000 min, the gas flow in the separated case is higher than that in the uniform (Fig. 4) and is mainly from the inpedestal region. Thus, the influx of gas into the metal inventory for the inpedestal region of the separated case is higher than that of the uniform case and more releases occur.

Of the remaining fission products not shown, oxides of cesium and niobium are volatilized completely, behaving much like CsI in Fig. 5. The La and Ce groups follow this general pattern of the oxides in Fig. 5, but only about 1% of these groups are released in either case. None of the Ru group is released.

SUMMARY AND CONCLUSIONS

Calculations of corium/concrete reaction processes have been examined for two different configurations of BWR core debris. The standard model involving radially uniform (but axially separated) oxide and metal layers was compared with a model that assumed significant radial separation of oxides and metals.

Results indicate that larger releases of combustible gases (CO and H_2) are produced in the uniformly distributed case as compared to the radially separated case. On the other hand, larger releases of non-combustible CO_2 and H_2O and a greater total gas release are calculated for the radially separated case. The reason for this is the different chemical environment imposed on the metals due to differences in heat losses associated with the core debris in each geometry.

Of significance for fission product release are debris temperatures and total gas flow from the debris surface. The only oxide layer releases occur when temperatures exceed 1900 K during the first few hours of the transient. While the total cumulative gas releases for the uniform case are lower, the flows during the high-temperature stage are greater, although delayed somewhat, from those calculated for the separated case. Not surprisingly, the oxidic fission product releases for the uniform case are generally delayed, but more severe, than those for the separated case. In both cases, all cesium and iodine are released completely, although the release is delayed somewhat in the uniform case.

The fission product release for the metallic debris contrasts with that of the oxidic debris. The metal debris temperature for the uniform case is calculated to be substantially higher than that of the separated case, leading to a higher Te release. Other metals are not released in significant quantities in either case, since even the uniform case metal temperature stayed below 1800 K for most of the calculation.

It is seen from the results of this work that the effects of lateral debris spreading on the drywell floor do affect the timing, composition, and magnitude of the release of debris gases and aerosols. The underlying reason for these differences is the location of the metallic debris relative to the oxidic debris and the metal chemistry involved. It is also apparent that the phenomenon of layer flip as calculated by CORCON plays an important role in metal chemistry. Furthermore, the reaction of elemental carbon produced as a result of the CORCON calculated coking reaction is observed to be the primary cause of the large combustible gas release subsequent to the depletion of Zr metal.

It should also be noted that extrapolation of these debris releases to the environment is not warranted because of the mitigating effects of aerosol deposition, settling, spray washout, etc. A complete calculation involving fission product transport and containment thermal hydraulics is required to make these assessments.

REFERENCES

1. C. R. Hyman and C. F. Weber, "Effects of Lateral Separation of Oxidic and Metallic Core Debris on the BWR MK I Containment Drywell Floor," NUREG/CR-4610, ORNL/TM-10057, pending publication.

2. R. O. Wooton, P. Cybulskis, and S. F. Quayle, "MARCH 2 (Meltdown Accident Response Characteristics) Code Description and User's Manual," NUREG/CR-3988, BMI-2115, August 1984.

3. R. K. Cole, Jr., D. P. Kelley, and M. A. Ellis, "CORCON-MOD2: A Computer Program for Analysis of Molten-Core Concrete Interactions," NUREG/CR-3920, SAND84-1246, August 1984.

4. D. A. Powers, J. E. Brockmann, and A. W. Shiver, "VANESA: A Mechanistic Model of Radionuclide Release and Aerosol Generation During Core Debris Interactions with Concrete" (Draft), NUREG/CR-4308, SAND85-1370, September 1985.

Table 1. *Comparison of calculated results for uniform and laterally separated debris. Cumulative gas released at end of calculation (1500 min)*

	Uniform	Inpedestal	Expedestal	Inpedestal + expedestal
		Gas release (kg-moles)		
CO	448	118	193	311
H_2	401	76	296	372
CO_2	52	258	6	264
H_2O	43	222	5	227
Totals	944	674	500	1174
		Mole fraction of gas release		
CO	0.47	0.18	0.39	0.26
H_2	0.42	0.11	0.59	0.32
CO_2	0.06	0.38	0.01	0.23
H_2O	0.05	0.33	0.01	0.19
Totals	1.00	1.00	1.00	1.00

Table 2. Fission products in core debris at the time of vessel failure

	Inventory (kg)		
Element	Uniform	Inpedestal	Expedestal
Xe	54.22	51.51	2.71
Kr	0.40	0.38	0.02
Te	26.9	1.35	25.55
Ba	108	103	5.4
Sr	72.6	69.0	3.6
Mo	263	13.2	250
Nb	3.52	3.34	0.18
I	3.51	3.33	0.18
		Cs Group	
Cs	32.3	30.7	1.6
Rb	3.98	3.78	0.20
		Ru Group	
Ru	191	9.6	181.4
Pd	94.3	4.7	89.6
Rh	35.5	1.8	33.7
Tc	64.2	3.2	61.0
		La Group	
La	102.2	97.1	5.1
Nd	304.5	289.3	15.2
Pr	90.8	86.3	4.5
Sm	57.0	54.2	2.8
Y	40.2	38.2	2.0
		Ce Group	
Ce	231	219.5	11.5
Pu	886	842	44.3

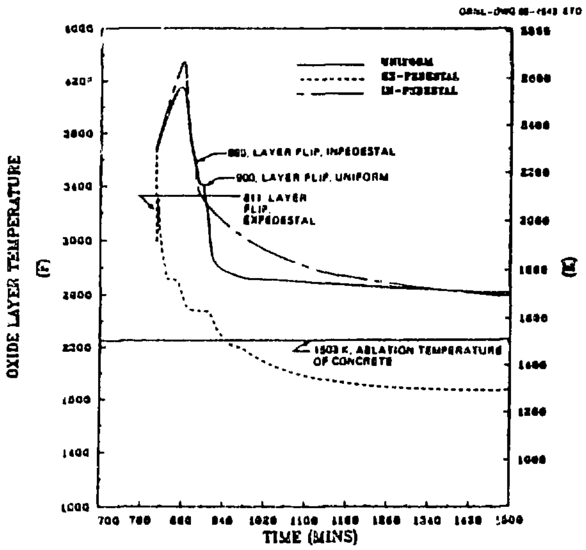

Figure 1. Oxide layer temperature for uniform and separated cases.

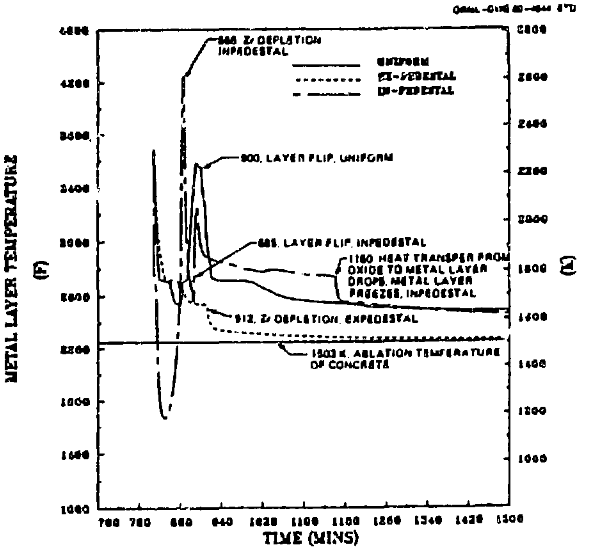

Figure 2. Metal layer temperature for uniform and separated cases.

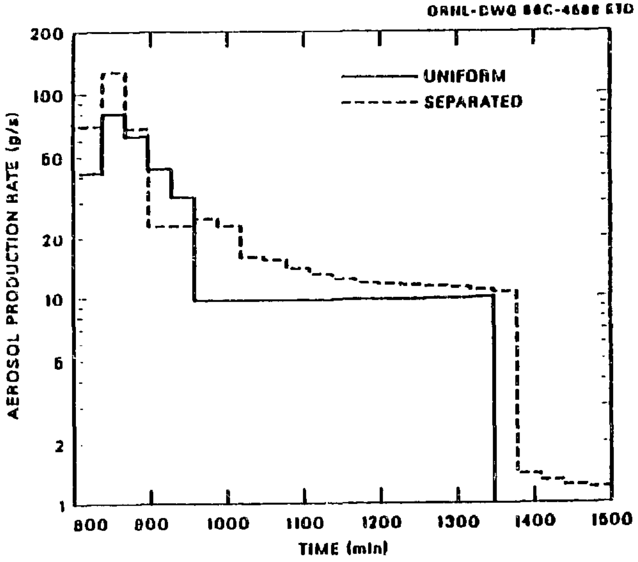

Figure 3. Total aerosol release rate from the debris for the uniform and separated (inpedestal + expedestal) cases.

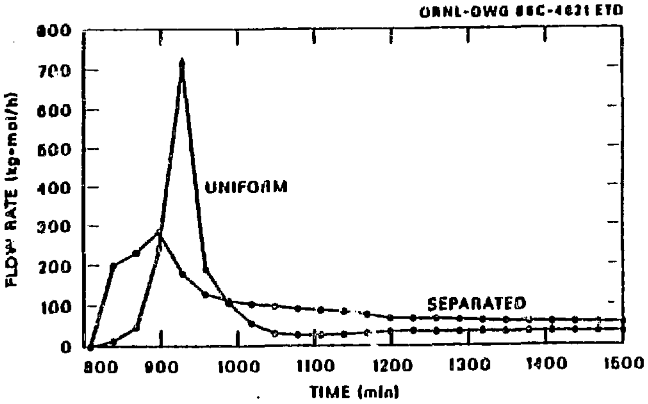

Figure 4. Total gas release rate ($CO + H_2 + CO_2 + H_2O$) from the debris surface for the uniform and separated (inpedestal + expedestal) cases.

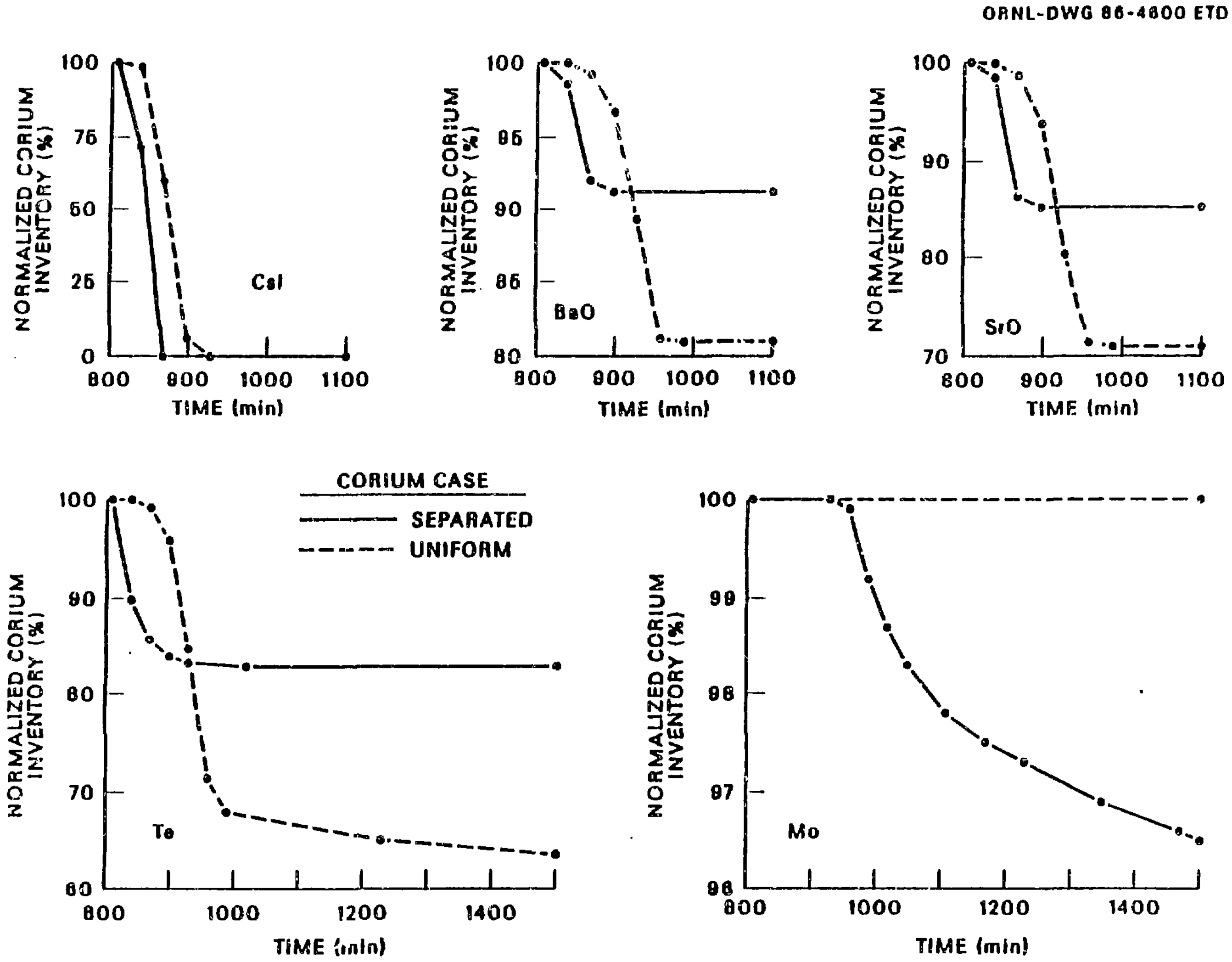

Figure 5. Debris fission product (CsI, BaO, SrO, Te, Mo) inventories for the uniform and separated (inpedestal + expedestal) cases.