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SEVERE ACCIDENT RISK MINIMIZATION STUDIES FOR THE ADVANCED NEUTRON SOURCE (ANS) REACTOR PLANT AT THE OAK RIDGE NATIONAL LABORATORY

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Abstract

This paper discusses salient aspects of severe accident related phenomenological considerations, scoping studies, and mitigative design features being studied for incorporation into a high-power research reactor plant. Key results of scoping studies on steam explosions, recriticality, core-concrete interactions, and containment transport are highlighted. Evolving design features of the containment are described. Containment response calculations for a site-suitability basis transient are presented that demonstrate acceptable source term values and superior containment performance.

INTRODUCTION

Oak Ridge National Laboratory's (ORNL's) Advanced Neutron Source (ANS) will be a new user facility[1,2] for all kinds of neutron research, centered around a research reactor of unprecedented ($\sim 10^{20}$ neutrons/m^2-s) neutron beam flux. A defense-in-depth philosophy has been adopted. In response to this commitment, ANS Project management initiated severe accident analysis and related technology development early-on in the design phase itself. This was done to aid in designing a sufficiently robust containment for retention and controlled release of radionuclides in the event of such an accident. It also provides a means for satisfying on- and off-site regulatory requirements, accident-related dose exposures, and containment response and source-term best-estimate analyses for level-2 and -3 Probabilistic Risk Analyses (PRAs) that will be produced. Moreover, it will provide the best possible understanding of the ANS under severe accident conditions and consequently provide insights for the development of strategies and design philosophies for accident mitigation, management, and emergency preparedness efforts.

This paper describes salient aspects of the ANS system design, results of focused severe accident scoping studies, efforts to identify mitigative design features, and strategies for reduction of the consequences of severe accidents in the ANS. Thereafter, the results of containment response calculations for a licensing basis transient are presented.

ANS SYSTEM DESIGN

The ANS is currently in the conceptual design stage. As such, design features of the containment and reactor system are evolving based upon insights from ongoing studies. Table 1 summarizes the current principal design features of the ANS from a severe accident perspective, in comparison with ORNL's High Flux Isotope Reactor[3] (HFIR) and a commercial Light-Water Reactor (LWR). As seen in Table 1, high-power-density research reactors can give rise to significantly different severe accident issues. Specifically, the ANS reactor will use about 15 kg of highly enriched (~ 93 m/o U-235) uranium silicide fuel in an aluminum matrix with a plate-type geometry, and a total core mass of 100 kg. The power density of the ANS will be about 2 to 3 times higher than that of the HFIR, and about 50 to 100 times higher than that of a large LWR. Such features have led to increased attention being given to phenomenological considerations dealing with steam explosions, recriticality, core-concrete interactions, core melt progression, and fission-product release. However, as opposed to power reactors scenarios, overall containment loads from hydrogen generation and deflagration are relatively unimportant for the ANS.

A schematic representation of the reactor and containment is given in Figure 1. The reactor core is enclosed within a so-called core pressure boundary tube (CPBT) and enveloped in a reflector vessel. As seen in the figure, this reactor system is immersed in a large pool of water. Experiment and beam rooms for researchers are located on the first and second floors, which are connected to the third floor high-bay region via rupture disk. The subpile room housing the control rod drive mechanisms is also connected to the third floor via lines with a rupture disk in between. The approximately 95,000-m^3 primary containment of the ANS consists of a 25-mm steel shell housed in a 0.8-m-thick reinforced concrete secondary containment wall with a 1.5-m gap in between. The targeted design leak rate for the primary containment is 0.5 vol %/day (to the annulus), whereas, for the secondary containment the design leak rate is 10 vol %/day. Annulus flow is exhausted through vapor and aerosol filters. The containment isolation system is designed to automatically initiate closure of isolation valves on lines that penetrate the primary containment wall.

ANS SEVERE ACCIDENT RISK MINIMIZATION STUDIES

Based upon the salient features of the ANS identified in Table 1, relevant severe accident issues that have been identified are:

- Fuel-Coolant-Interactions (FCIs) (e.g., steam explosions),
- Recriticality,
- Debris noncoolability and ablation of structural boundaries,
- Core-Concrete-Interactions (CCI),
- Gas detonation, and
- Containment overpressurization failure.

Results from focused studies on the issues listed above are summarized in the following sections.

Study and Prevention of Steam Explosion Loads in ANS

The study of FCIs is of particular interest to ANS safety due to well-known propensity for molten aluminum to interact explosively with water.[4,5] Such reactions can cause large amounts of mechanical energy to be generated within a very short time frame, creating missiles and shock waves that may damage the containment. Results of a recently completed scoping study[5] for the ANS have indicated that the CPBT and reflector vessel (made of aluminum) very likely would rupture under predicted FCI loads generated for a variety of severe accidents. Severe accidents considered in this focussed study included anticipated transients without scram (ATWS), reactivity excursions, and debris melting under decay heating conditions. This study clearly indicated the need for incorporation of a well-characterized set of mitigative features. Merely increasing the thickness or changing the materials of the CPBT are in conflict with the main mission of the ANS (i.e., high thermal neutron flux) and were thus not options. Considerations are being given towards the material of choice for the reflector vessel, in conjunction with the strategic introduction of a void volume for reduction of pressurization loads. More sophisticated evaluations are being made to give indications on the relative merits of the energy absorption capabilities of various system structures, including the reactor coolant system (RCS). Based on results of these studies, judiciously positioned missile shields or pressure relief valving will be considered to minimize the risk for containment failure or damaging blowdown loads.

For the ex-vessel phase of steam explosions (especially in the subpile room), evaluations are being made for the introduction of strategic flooding. As a basic recommendation, system operation is being prescribed to minimize situations in which large quantities of molten debris and water come into contact. If, for example, the core debris must be cooled with water, a flooding strategy is recommended that employs a pulsed injection mode so that if an explosive FCI does occur, the amount of water present will be limited. Another strategic flooding method would employ sprays with appropriately timed injection that causes sufficient quenching but significant steam blanketing at the water-fuel interface to prevent triggering of explosions.

As is well-known, the appropriate use of additives[4] to the water can suppress the steam explosion triggering potential to a negligibly low value. Therefore, the use of additives to the water used for flooding strategies is also under consideration in ex-vessel situations. Another mitigative feature is the use of surfactants which may assist in inhibiting steam explosion occurrence. Presently, severe accident researchers in conjunction with ANS designers are considering the feasibility of using particular preventive mechanisms in the overall context of plant design. Thereafter, a focussed experimental-cum-analytical effort will be undertaken as needed to quantify, qualify, and validate such a mitigative design feature.

Prevention and Mitigation of Debris Recriticality Loads in ANS

As shown in Table 1, the ANS will use about 15 kg of highly enriched U-235 fuel encased in an aluminum matrix. Under certain accident scenarios the fuel material can relocate out of the control region and under the appropriate configuration, may undergo a prompt recriticality transient (an aspect that is usually considered a non-issue for power reactors). A scoping study has been conducted to evaluate such a potential for the ANS using the KENO5-SCALE neutronic code system[6] at ORNL. This preliminary recriticality study for the ANS core debris in various postulated post-accident configurations within the RCS has indicated that it might theoretically be possible to insert significant excess reactivity (i.e., 10 dollars worth). This was found to be the case only for dispersed configurations where all of the fuel (i.e., 15 kg of U-235) was involved. An alternate calculation with about 4 kg of fuel dispersed in a D_2O medium resulted in a k_{eff} of only 0.85. The amount of fuel which needs to be dispersed to give a k_{eff} value of 1.0 has yet to be evaluated for various thermal-hydraulic conditions. All lumped fuel configurations remained significantly subcritical for the conditions studied. These evaluations demonstrated, to the extent they were representative of expected conditions, that a mechanism should be found to prevent dispersion of a large enough portion of core debris during severe accidents. If fuel dispersion is inevitable, it is clearly preferable to introduce design features that allow only small portions to disperse. Other options considered relate to the introduction of neutron poisons (e.g., borated pipes) in selected RCS regions.

This is a clear case where a design-fix, that "will" prevent recriticality, is far more preferable to an extensive research program that "may" solve the problem. This is because not much is known on modeling and analysis of "transient" debris recriticality events.

As mentioned above, a principal aspect dealing with debris recriticality in the ANS during severe accidents requiring investigation deals with debris dispersion. Research efforts are thus to be focused toward analytically quantifying melt progression aspects with the potential for leading to recriticality, possibly coupled with qualification via scaled experimentation.

Prevention and Mitigation of CCI and Combustible Gas Detonation Loads

As mentioned previously, the potential generation of combustible H_2 in the ANS from oxidation of the aluminum in the fuel plates is significantly lower than for power reactors. However, additional

CO and H_2 gases can also be generated during the CCI stage. Fortunately, our scoping studies show that even if all the generated gases were to uniformly fill the primary containment, the concentration level would still be less than 1% by volume. This is significantly lower than the level necessary for deflagration (8 vol %) or detonation (13 vol %). However, the possibility exists for generating high concentrations (i.e., greater than the detonation limits) of combustible gases in selected containment regions. Specifically, this becomes a real possibility in the subpile room during CCI if the basemat is made with limestone-common sand concrete. For such conditions, the use of an inert atmosphere combined with igniters in selected volumes most susceptible to the buildup of detonation quantities of combustible gases has been strongly recommended. This will be considered for feasibility of introduction within the overall context of plant design.

Another means for preventing detonation loads in critical regions was studied in conjunction with minimizing concrete ablation and gas generation during CCI. For the ANS conditions, our scoping studies have shown that the threat to containment integrity from CCI loads can be prevented or mitigated if the surface lining of the basemat were made with alumina concrete coupled with the flooding strategy described above. Details of the study can be found in Reference 7. Another means considered for minimizing CCI would be to design the subpile room cavity to spread the core debris sufficiently for maintaining coolability (i.e., interface temperature below the concrete ablation temperature). This was not considered feasible from operational considerations and also because the amount of debris spreading on a level surface is limited by surface tension.

The most promising approach toward eliminating threats from CCI-generated loads for the ANS would rely on lining the basemat of the subpile room with alumina concrete. The depth of this lining (for a conservatively scoped debris-concrete configuration) should be greater than the thermal boundary layer thickness as a minimum, combined with an appropriate flooding strategy. Strategic flooding would achieve the purposes of preventing steam explosions, quenching the debris to prevent CCI, and finally to also assist in scrubbing fission products. It is recognized that the qualification and validation of this mitigative feature would require focused analytical and experimental efforts. In conjunction with this prescription, we have introduced strategically positioned igniters to burn off the greatly reduced (albeit potentially damaging) amounts of combustible gases in confined volumes.

Measures for Minimization of Source Term, Debris Noncoolabiltiy and Structural Ablation

From an obvious perspective, for severe accidents with significant fuel melting, the best way to minimize the source term is clearly to keep the fission products bottled up in the RCS itself. This requires maintaining the debris in a coolable state. For the purposes of this discussion, we define coolability to represent a thermal condition where the interface temperature between the debris and structure under attack is lower than the structure's melting temperature. Scoping calculations have shown that in order to achieve this for ANS debris with its high-power density (viz., more than 50 to 100 times that of power reactor debris), the debris would need to be sufficiently dispersed, and covered with water. Details will be discussed in a report[8] to be published later. Dispersion would effectively increase heat transfer surface area. The precise degree of dispersion necessary is clearly a function of several parameters (viz., debris decay power level, structural material and geometry under attack, coolant thermal-hydraulic conditions, etc.). In any case, it is evident that a means should be engineered in the system to ensure that the debris does not relocate to regions in a lumped geometry if noncoolability is to be avoided. However, this approach is in conflict with design needs for minimizing recriticality loads, which can be initiated in dispersed geometries. An iterative approach is being followed toward identifying an optimized set of design features.

As is well-known, a simple but highly effective technique for reducing the source term utilizes the natural tendency of water to provide fission-product scrubbing. Every effort is being made to make sure that wherever possible, fission products are released only through a water pool. For this and other reasons, the ANS reactor vessel is located in the bottom of a large pool. Most of the RCS piping also passes through water-filled pools. It should be noted however, that the scrubbing function is dependent on and, in some cases, very sensitive to key parameters such as pool subcooling, depth, and pH, as well as the fission-product form. Therefore, the design attributes of such water pools will take into account these parameters to provide the needed scrubbing capability.

Measures for Minimization of Overpressurization Failure

It is recognized that no amount of filtration or containment capability can help if the containment boundary fails catastrophically via overpressurization. Several possible means by which this may occur involve loads generated either due to explosions or from events such as steaming or combustible gas deflagration. Prevention of containment failure from explosive events was discussed earlier in the sections dealing with FCI and recriticality prevention. Here we discuss aspects dealing with minimization of risks from overpressurization failure due to relatively static loads.

Due to the large size of the ANS containment (> 95,000 m^3), containment transport calculations show that pressurization from nonexplosive conditions will not cause overall primary containment shell failure. However, for smaller compartments, such as the subpile room where a CCI event can quickly cause overpressurization failure of containment walls, pressure-relief mechanisms have been selected. Specifically, a rupture disk is allowed to open up a flow path from the subpile room to the high bay volume if the subpile room pressure goes above 115 kPa (2 psig). Another similar rupture disk allows pressure relief for the large high bay volume if the pressure exceeds 115 kPa (2 psig); that is, if the pressure in the high bay volume exceeds 115 kPa (2 psig), a rupture disk opens up to allow expansion into the first and second floor volumes. Such a zoning arrangement also serves the important purpose of facilitating personnel evacuation from the first and second floor volumes in the event of a severe accident. The effects of such a designed pressure-relief mechanism will be evident from results presented in the next section, displaying containment response characteristics for a site-suitability basis transient.

The large containment volume of the ANS coupled with the relatively smaller quantities of heat-generating fission products (about 10% of that for large power reactors) and the designed pressure-relief mechanisms make engineered safety features such as sprays unnecessary. However, fan coolers will be considered for volumes such as the subpile room where even if appropriate pressure relief is provided, the atmosphere may reach high temperatures during deflagration events.

ANS CONTAINMENT RESPONSE DURING A SITE-SUITABILITY BASIS TRANSIENT

This section describes the thermal-hydraulic and radionuclide transport modeling aspects along with analyses conducted for evaluating the ANS containment response for a site-suitability basis transient. The scenario to be modeled follows the prescriptions given by the 10 CFR 100 guidelines outlined in Reference 9. It is hereafter referred to as the CFR100 scenario.

The MELCOR severe accident analysis code[10] was used to develop an overall representation of the ANS containment. The model, consisting of 11 control volumes, 15 flow paths, and 21 heat structures (representing walls, ceilings, shells, and miscellaneous materials) of various shapes, is shown in Figure 2. A fan model has also been included to account for flow through the large annulus gap between the steel shell and outer containment. Aerosol and vapor filtration processes are also modeled, as are various complex aerosol and vapor transport phenomena associated with the severe accident scenario being evaluated.

The CFR100 scenario was analyzed assuming an intact primary and secondary containment. Iodine and aerosol filter trains have been incorporated to provide retention (of halogens and particulates) with decontamination factors of 100 and 200, respectively. Leakage rates of 0.5 vol %/day from the primary containment to the annulus (under design pressure difference), and 10 vol %/day from the annulus to the environment were modeled. The modeling of annulus leak rate of 10 vol %/day was performed by conducting an inverse calculation. That is, the exhaust rate of 10 vol %/day was specified as a boundary condition, and resulting pressure distributions in the annulus were back calculated. At the start of the calculation, 100% of the noble gases and 25% of the halogen inventory were sourced into the high-bay volume atmosphere as vapors. In addition, 1% of the remaining radionuclides were sourced into the high-bay atmosphere as aerosols. The remainder of the radionuclides were assumed to "stay" in the reactor pool volume of 100 m^3 without volatilization. Such a prescription provides for the maximum possible heat generation for steaming purposes.

Salient results of MELCOR calculations are shown in Figures 3 through 7. Pressurization traces for various regions of the containment are shown in Figure 3. As seen therein, high-bay volume pressure rises quickly after pool steaming begins in about 4 hours. Thereafter, rupture disks provide pressure relief when a pressure difference of 112 kPa (2 psig) is reached. Eventually, the entire containment volume pressure levels off at about 121 kPa (2.75 psig).

Figure 4 provides results of temperature rise in various containment regions. As the figure shows, the atmospheric temperatures in the high-bay and annulus regions can get quite high due primarily to steam condensation and radionuclide settling on various heat structures. Figure 5 shows the transient variation of total radionuclide mass deposition onto heat structures in the containment. As can be seen, more than 0.5 kg of the radionuclides that were originally deposited in the high-bay-area are deposited onto heat structures within the first 15 hours of the transient.

Figures 6 and 7 show the variation of the radionuclide source term (after passing through filter banks). As seen from Figure 6, only about 1% of the noble gases, and less than 0.0007% of the halogen inventory is released over 70 hours. Figure 7 shows that a negligible amount (i.e., less than 10^{-7}%) of nonvolatile elements escape to the environment over 70 hours. Most of the nonvolatile release occurs soon after the high bay area volume pressure exceeds 112 kPa (2 psig).

The results presented above indicate that the negligible amounts of radionuclide releases will allow the ANS to meet site suitability criteria by a good margin. The low releases are essentially due to the leak-tight nature of the containment, coupled with halogen and aerosol removal by the filter banks.

SUMMARY and CONCLUSIONS

To summarize, this paper has discussed salient aspects of severe accident related phenomenological considerations that have been considered for developing designed risk minimization features in the ANS. Key results from scoping and other studies on steam explosions, recriticality, CCI, containment transport, and pressurization have been described along with evolving design features of the one-of-a-kind ANS containment. Table 2 summarizes several recommendations that have been made in this paper for mitigating and/or managing containment loads from severe accidents in various phenomenological areas. As noted in Table 2, a comprehensive series of design features are being researched for incorporation into the design of the ANS for risk minimization from severe accidents.

The results from the CFR100 scenario with an intact containment indicate that selective overpressurization in the ANS will be avoided by judicious use of pressure-relief mechanisms. Negligibly low values of radionuclides are shown to be released to the environment, indicating the effectiveness of natural heat sinks and structural deposition (in addition to filtration).

It is recognized that the overall risk will have to consider several severe accidents in various release categories. However, it is expected that when the designed mitigative features summarized in Table 2 are accounted for in the overall context of plant design, the ANS will demonstrate overall safety by a wide margin. That is, it will be shown to be safe from both probabilistic and deterministic standpoints (viz., negligibly low values of risk and no fatalities or injuries if a severe accident did occur).

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Table 1. Severe Accident Characteristics of the ANS and other Reactor Systems

Parameter	Commercial LWR	HFIR	ANS
Power [MW(t)]	2600	85	300
Fuel	UO_2	U_3O_8-Al	U_3Si_2-Al
Enrichment (m/o)	2-5	93	93
Fuel Cladding	Zircaloy	Al	Al
Coolant/Moderator	H_2O	H_2O	D_2O
Coolant Outlet Temperature (°C)	318	69	92
Average Power Density (MW/ℓ)	<0.1	1.7	4.5
Clad Melting Temperature (°C)	1850	580	580
Hydrogen Generation Potential (kg)	850	10	12

Table 2. Summary of Recommendations for Design Fixes and Mitigative Mechanisms

Recommendation	Notes on Recommendation
Employ an ANS design that retards or traps fission product vapors and aerosols for minimization of the source term	Fundamental safety prescription
Design against selective overpressurization in containment compartments	Carefully engineered venting paths with selective compartmentalization without overpressurization is desirable to provide more time for evacuation as well
Carefully consider a more robust reflector tank material than aluminum	Containment of steam explosion pressure pulses, and also radionuclide dispersion
Consider incorporation of a missile shield or other energy-absorbing mechanism	If evaluations indicate a high probability of energetic missile generation from explosive events
Alter the design and operation to minimize possibilities for molten core debris coming in contact with large amounts of water in the subpile room, employ strategic flooding or timed-sprays for subpile room	Improves quenching, prevents explosive fuel-coolant-interactions, and prevents core-concrete-interactions
Consider use of additives to sufficiently increase viscosity of water used for flooding strategies	Minimizes triggering potential; can be used in conjunction with an appropriate surfactant
Find a mechanism that prevents uniform dispersion of core debris in reactor coolant system to prevent recriticality. Another consideration would use borated-water-injection system as in power reactors, or borated structures	Recriticality prevention via design and operation
Adopt in-depth measures to prevent and mitigate combustible gas detonation	This includes igniters (e.g., in subpile room) to burn combustible gases as they evolve and before detonation concentrations are reached
Consider either confining debris (using a core catcher) or dispersing it to avoid noncoolability and unacceptable structural ablation	Iterate with severe accident researchers to determine location and validity of the installed mechanism
Line the subpile room floor with alumina concrete and provide for strategic flooding to minimize structural ablation and production of combustible gases	Unless operational considerations dictate otherwise

Table 2. Summary of Recommendations for Design Fixes and Mitigative Mechanisms (cont.)

Recommendation	Notes on Recommendation
Make every effort to design flow paths to ensure that released fission products are transported only via passage through a water pool	Iterate between designers and severe accident researchers to optimize the scrubbing potential of the water pool
Design to ensure that the radionuclides in the production target rods do not escape from the reactor cooling system	Work needs to be done iteratively between designers and severe accident researchers
Address phenomena such as combustible gas stratification via mixing mechanisms	For prevention of detonable gas formation

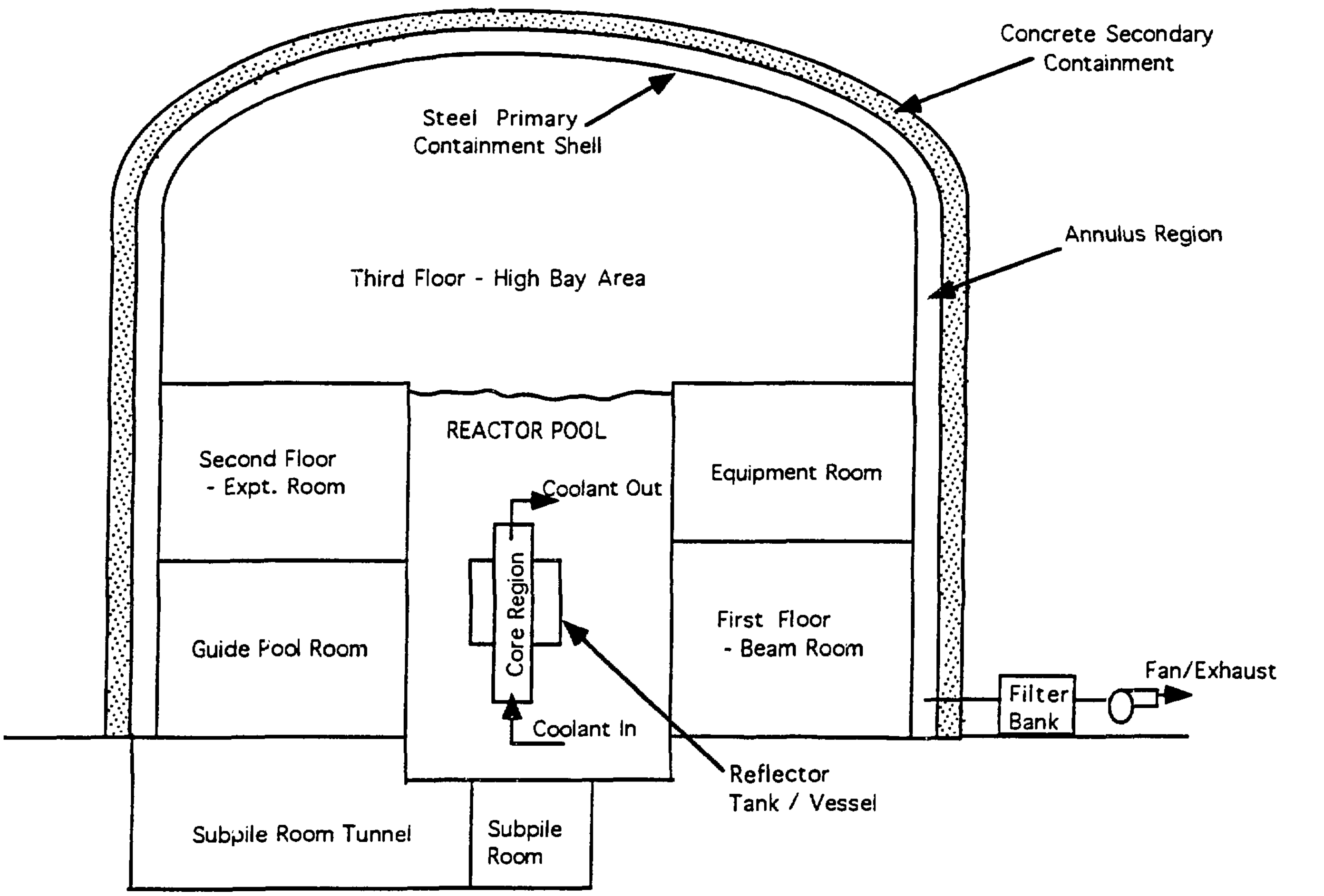

Figure 1. Schematic Representation of ANS Containment

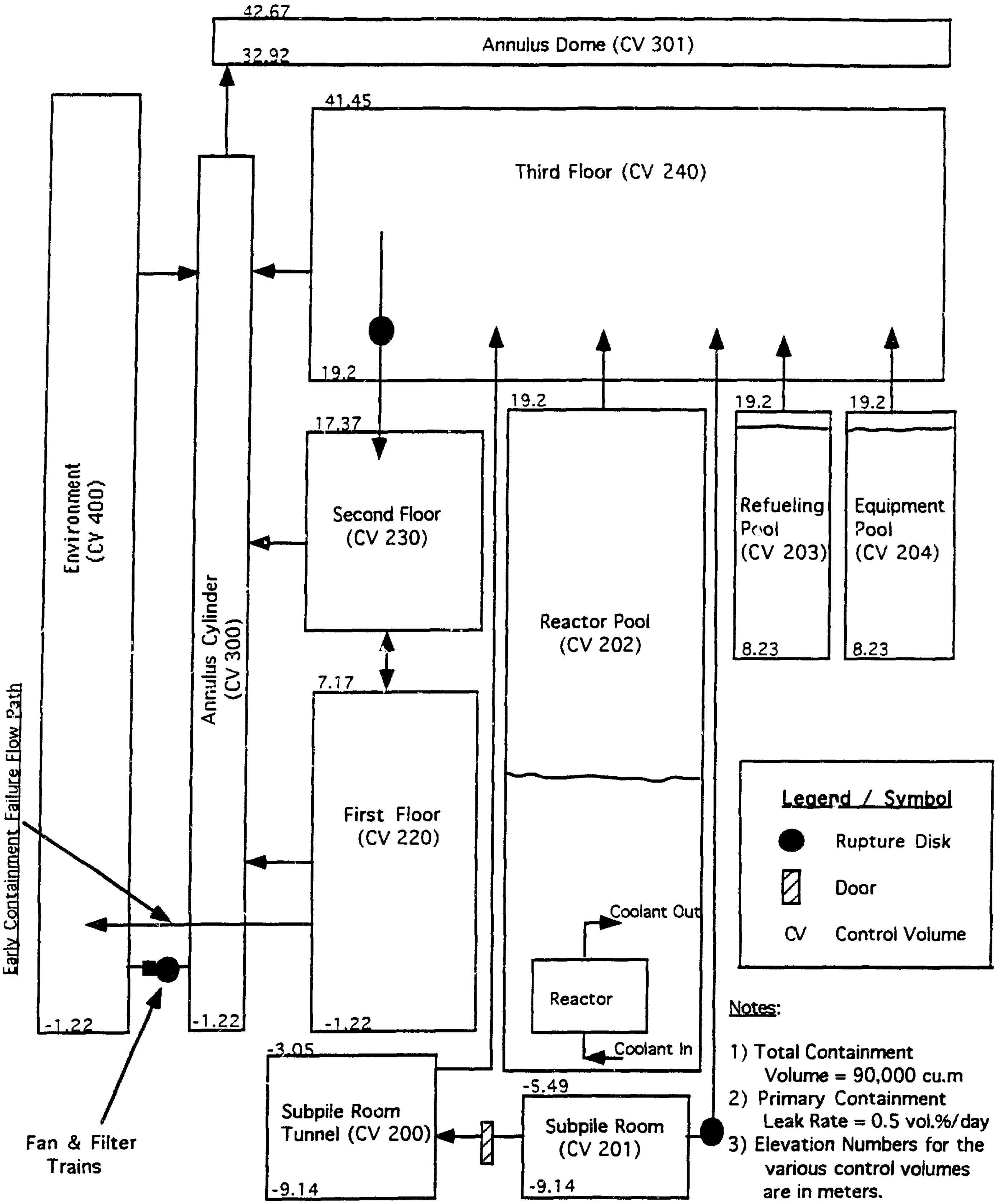

Figure 2. ANS Containment (MELCOR) Representation for Environmental Report

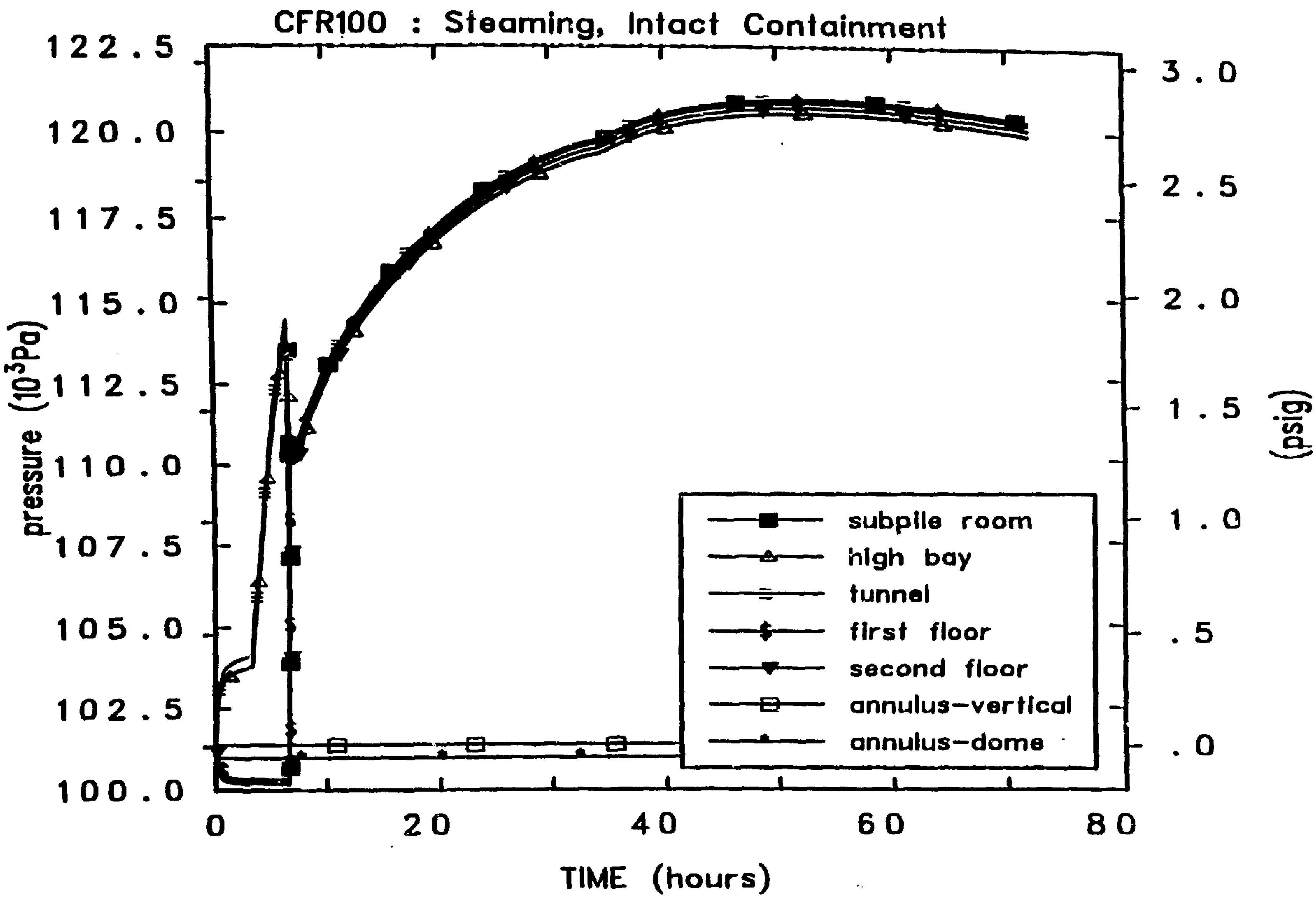

Figure 3 Variation of Containment Pressure vs Time for CFR100 Scenario

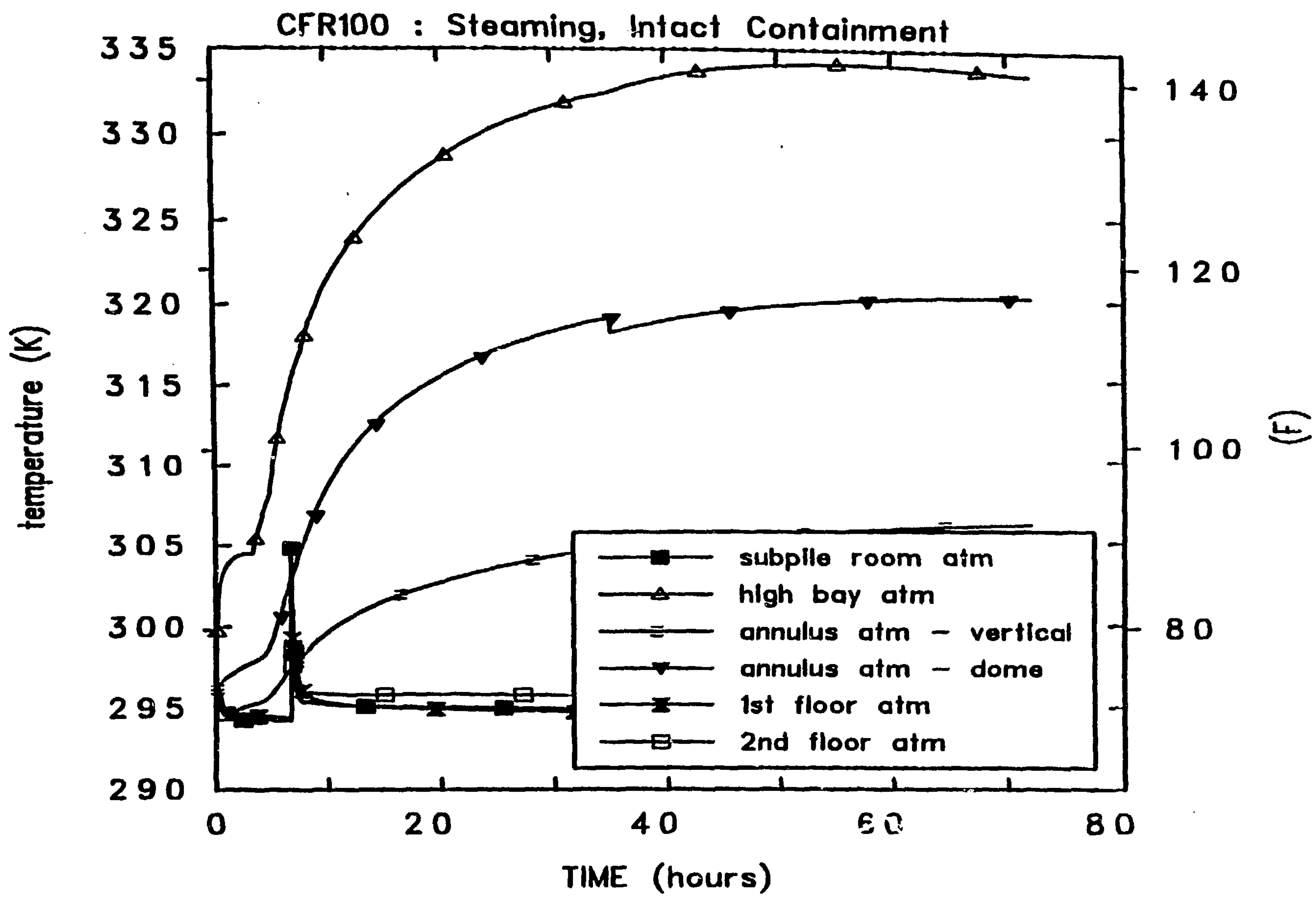

Figure 4 Variation of Containment Temperatures vs Time for CFR100 Scenario

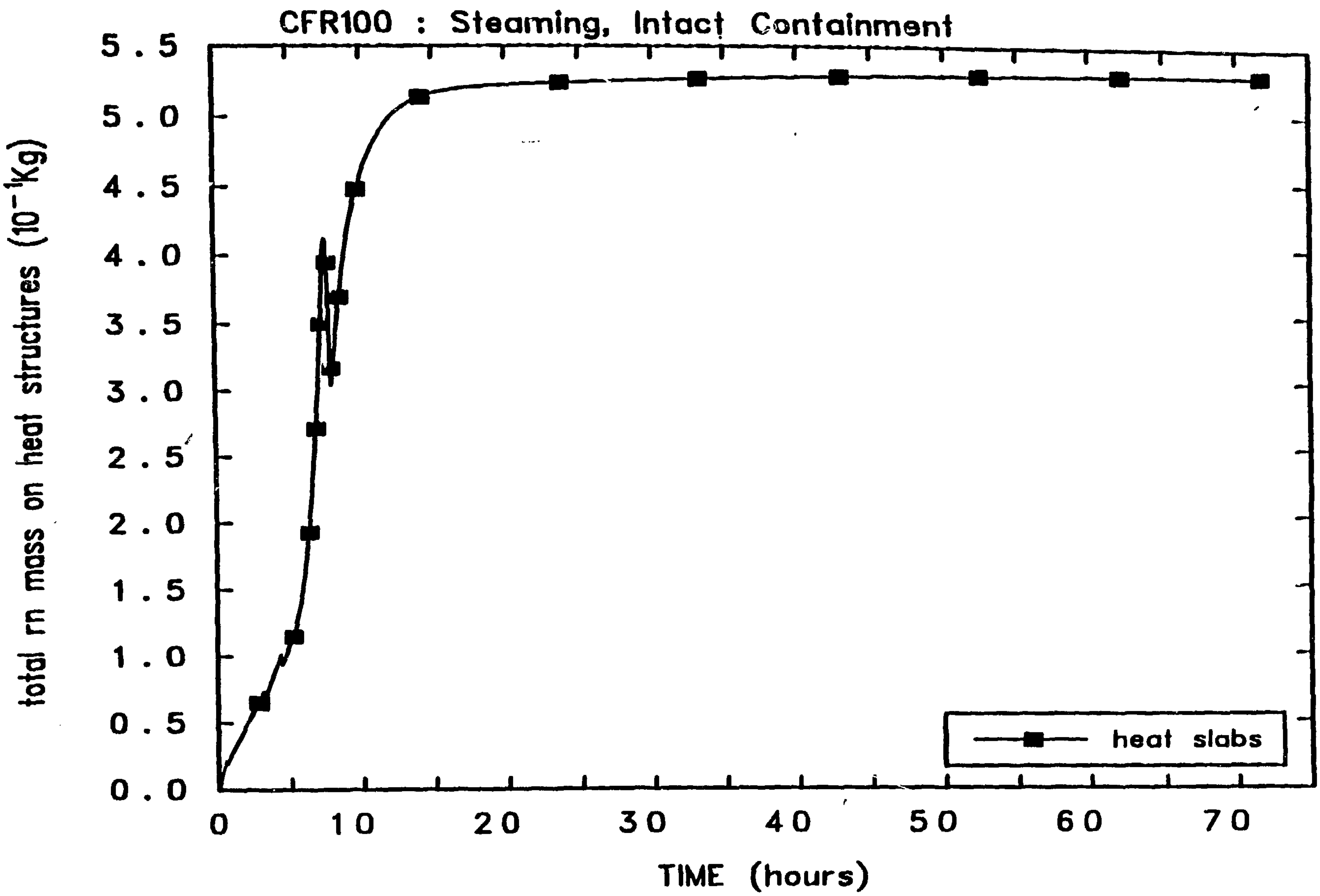

Figure 5 Variation of Total Deposited Radionuclide Masses on Containment Heat Structures vs Time for CFR100 Scenario

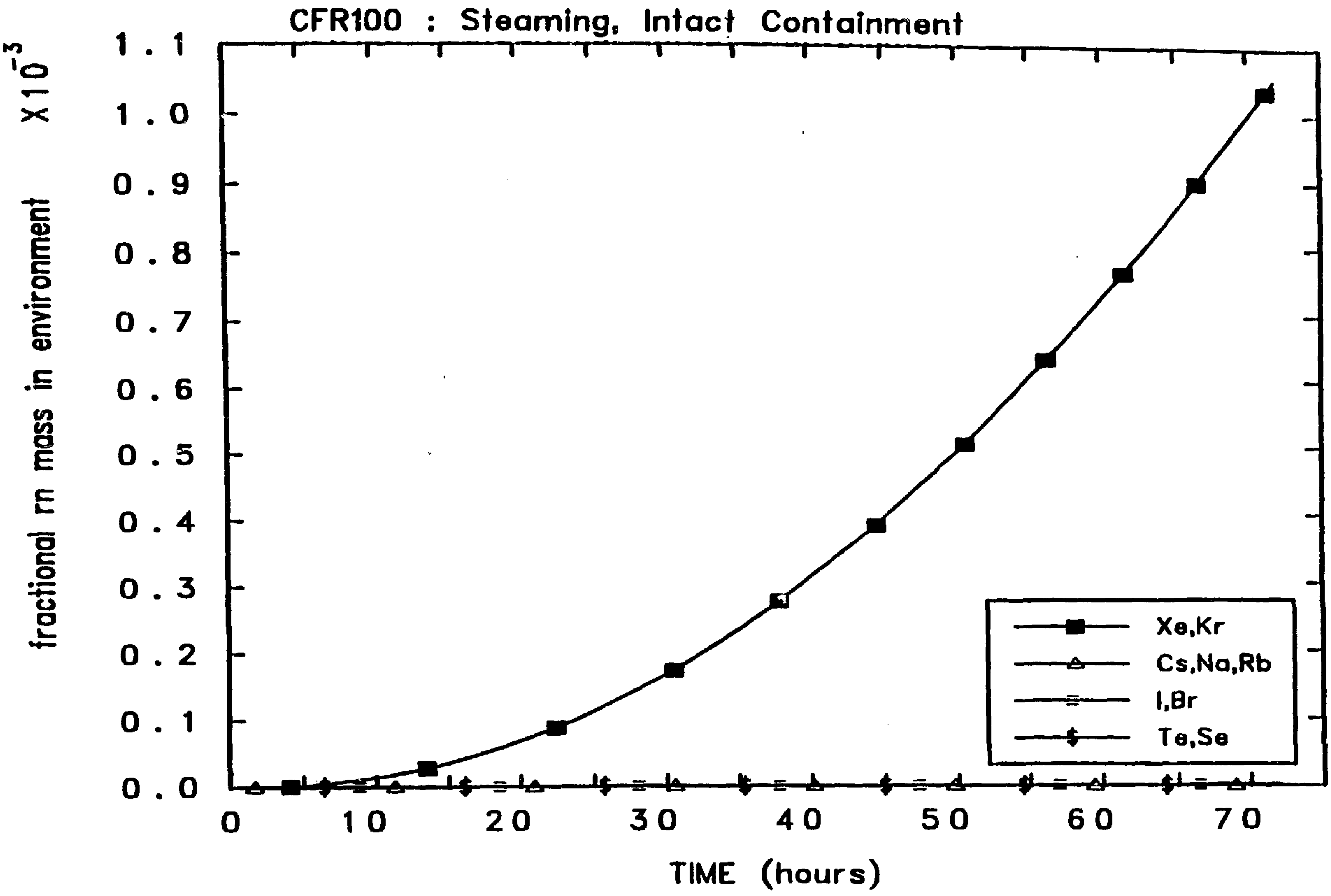

Figure 6 Variation of Volatile Fission Product Releases to Environment from Containment vs Time for CFR100 Scenario

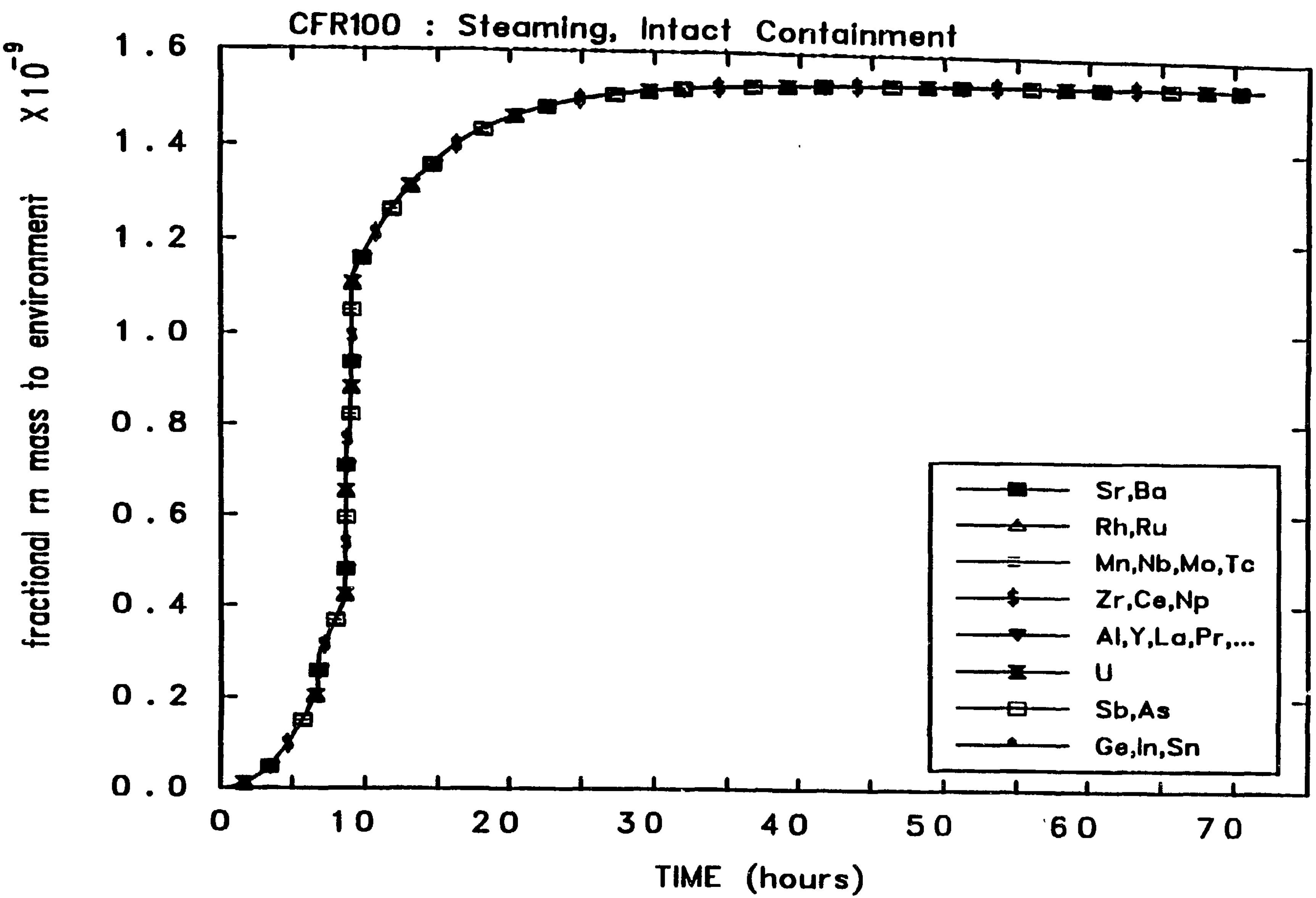

Figure 7 Variation of Non-Volatile Fission Product Releases to Environment from Containment vs Time for CFR100 Scenario