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SCOPING STUDIES OF VAPOR BEHAVIOR DURING A SEVERE ACCIDENT IN A METAL-FUELED REACTOR*

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ABSTRACT

Scoping calculations have been performed examining the consequences of fuel melting and pin failures for a reactivity-insertion type accident in a sodium-cooled, pool-type reactor fueled with a metal alloy fuel. The principal gas and vapor species released are shown to be Xe, Cs, and bond sodium contained within the fuel porosity. Fuel vapor pressure is insignificant, and there is no energetic fuel-coolant interaction for the conditions considered. Condensation of sodium vapor as it expands into the upper sodium pool in a jet mixing regime may occur as rapidly as the vapor emerges from the disrupted core (although reactor-material experiments are needed to confirm these high condensation rates). If the predictions of rapid direct-contact condensation can be verified experimentally for the sodium system, the implication is that the ability of vapor expansion to perform appreciable work on the system is largely eliminated. Furthermore, the ability of an expanding vapor bubble to transport fuel and fission product species to the cover gas region where they may be released to the containment is also largely eliminated. The radionuclide species except for fission gas are largely retained within the core and sodium pool.

INTRODUCTION

The Integral Fast Reactor (IFR) is an advanced concept of a sodium-cooled fast reactor having the core region submerged in a large pool of sodium at a pressure only slightly above atmospheric. In the reference design, the system uses sodium-bonded metal fuel in the core. Analyses have shown that the system is highly tolerant of severe, unprotected transients and is not likely to experience core disruption nor even fuel melting despite the low melting temperature of the U-15Pu-10Zr reference fuel ($T_{solidus}$ = 1423K).[1] This is due to inherent features of the system, especially the high thermal conductivity and expansion of the fuel. Nonetheless, it is possible to postulate transients such as unterminated reactivity insertion that are severe enough that the thresholds for fuel melting and pin failures may be surpassed. The purpose of these scoping studies was to examine the consequences of this postulated severe accident under conditions appropriate to IFR with metal fuel.

The blowdown of gas and vapor from failed pins into the coolant channels and the resulting gas/vapor expansion process have several aspects important to the overall accident sequence; namely, a) possible expulsion of the sodium coolant fronm the fuel assembly, b) possible dispersal of molten fuel from the core region by a drag-related sweepout process, c) possible acceleration of overlying sodium which may impact the vessel head causing damage, and d) possible transport of fuel and fission product species to the cover gas region where they may leak from the system. Hence, the pin blowdown and gas/vapor expansion may play varing roles insofar as determining reactivity changes during the accident due to coolant voiding and fuel motion, determining the conversion of expansion energy into mechanical work performed on the reactor head and vessel, and determining the early-time release of radionuclides to the reactor containment.

In previous analyses of vapor production and expansion effects performed for oxide-fueled cores, it has been considered that vapor is produced very suddenly in the core region, initially producing a pressure wave which propagates through the coolant, and subsequently accelerating a liquid slug as the vapor zone undergoes expansion.[2] The working fluid may be fuel vapor in some accident sequences, owing to the relatively small temperature difference of ~ 450K between the melting and boiling points for mixed oxide fuel. Hence,

in oxide cores, a reactivity insertion capable of causing rapid fuel melting may also cause significant fuel vapor pressure. Alternatively, the working fluid has also been considered to be sodium vapor, resulting from an extreme case of a fuel-coolant interaction (FCI) in which vapor is considered to be formed on an explosive time scale. In both cases, the vapor formation and expansion processes have been considered to occur on such a fast time scale that heat transfer from the vapor to surrounding structure and coolant during the expansion process was typically ignored. This picture is substantially different, however, for IFR with metal fuel. The metal fuel boiling point is ~3000°C above its melting point, and hence, metal fuel vapor pressure is not a significant factor. Additionally, application of the interface temperature criterion for a large-scale vapor explosion[3] indicates that the metal fuel temperature would have to exceed ~3000°C for an energetic interaction to occur, and this temperature is nowhere near approached in any reasonable postulated reactivity insertions. Hence, there appears to be no mechanism in IFR with metal fuel to give the large, rapid expansion processes characteristic of previous oxide-core analyses. The picture for the metal fueled system is a much more benign process involving channel boiling and pin blowdown effects. A key factor is that these processes may be sufficiently slow that heat transfer during the expansion phase may no longer be negligible. The possibility that the combined effects of a smaller vapor source plus vapor condensation both act to lessen the accident energetics and radionuclide release is being explored. Scoping studies have been performed to examine the disruption process in IFR, and the preliminary results are reported here. Although the design of IFR is not firmly established, representative parameters were selected based on the design of the Large Pool Plant (LPP), a pool-type sodium-cooled system wtih a nominal power of 3500 MWt (Figure 1).

PIN BLOWDOWN

The effects of pin failures insofar as release of gas and vapor into the coolant channels is examined first. The inventory of gaseous and volatile species in the fuel pins is estimated for these scoping calculations based upon a representative fuel assembly assumed to have burnup equivalent to one full-power year. A key feature of IFR with metal fuel is that the pins contain bond sodium which initially fills the fuel-to-cladding gap. During

operation the metal fuel swells, contacting the cladding at ~2 a/o burnup. Experience with this type of fuel in EBR-II has shown that ~ one-third the available porosity (75% smear density) contains bond sodium. During a temperature transient, this material behaves like a volatile species distributed throughout the fuel matrix. The total estimated core-wide inventories of gaseous and volatile species, including the sodium contained in the fuel porosity, are given in Table 1. The two-thirds of the bond sodium displaced from the gap and not contained in the porosity is not included in this table. The table conservatively considers that the species are present in their elemental form, although some compounds such as CsI are expected to be present. However, there is expected to be less compound formation in the metal fuel system than in the oxide fuel system owing to the relative lack of oxygen.[4] It can be seen from Table 1 that Xe, Cs, and bond sodium in the fuel matrix account for ~95% of the mole inventory of gaseous and volatile species. Hence, these are the key species insofar as gas/vapor blowdown from a failed fuel pin.

The blowdown of failed pins is predicted to evolve in two stages. During the initial release stage, predominantly fission gas from the fuel pin plenum region (~50 atm reference pressure) blows down through the breach site, and, depending upon the location of the breach, may carry little if any fuel into the coolant channels. Some release of gas and vapor from within the fuel is also expected. This initial gas release is expected to cause upward, and possibly downward channel voiding. During this initial blowdown the pin pressure is eventually reduced to the point that the saturation pressure of the bond sodium contained within the fuel mass is reached. For a fuel temperature of ~ 1300°C, characteristic of pin disruption conditions[5] (~100°C above the nominal melting temperature of the U-15Pu-10Zr fuel alloy), this occurs at a pin pressure of ~ 20 atm. Hence, the second stage of blowdown involves the flashing of sodium from within the molten region of the fuel, causing a temporary pressure plateau within the pin at ~ 20 atm. This flashing process is expected to be an important factor in ejecting molten fuel from the pin and in dispersing the fuel from the core region, although this remains to be demonstrated in TREAT and CAMEL tests. According to the relative molar inventories, Table 1, this second stage of blowdown is expected to involve a substantially larger vapor release than the predominantly gas release of the first stage.

CHANNEL BLOWDOWN

The rate of flow of the gaseous and vapor species axially through the subassembly is estimated based upon the following simplified considerations. The cladding breaches are assumed to offer negligible resistance to flow during the sodium flashing stage, and hence, the channel pressure at the breach site is assumed to build up to P_{sat} (20 atm) during the channel blowdown. This pressure exceeds the sodium pump head of ~ 10 atm, and hence, temporary stoppage and reversal of sodium flow through the subassembly would follow. The relative inertial lengths for upward and downward slug expulsion from the disruption zone are such that voiding will progress much more rapidly in the upward direction.[6] The subassembly may not void completely in the downward direction, and under these conditions the downward expansion process is of small importance compared to the upward expansion. For the present scoping calculations the upward sweepout of fuel and the plateout of fuel in the channel are ignored; ie, the upward blowdown takes place as a single-phase flow through unobstructed coolant channels. (Two-phase flow effects and fuel plateout effects, if considered, would both act to slow down the rate of gas/vapor flow into the upper sodium pool). Condensation is also ignored during this stage of the vapor flow. The vapor expands to a pressure of ~2 atm at the top of the subassembly. Using Shapiro's analysis to calculate the flow of a compressible gas through a long channel with friction,[7] the estimated blowdown flowrate is ~ 2.8 kg/s for the disrupted subassembly. The flow is predicted to be choked, but just barely so. The duration of this blowdown stage is predicted to be short, of the order of 0.1 s. The peak efflux velocities in the coolant channels are calculated to be ~ 100 m/s at the disruption zone, increasing to ~ 800 m/s at the tops of the pins. The vapor exits the subassembly duct through the top opening (~ 8 cm dia) whereupon it enters into the upper internal structure (UIS) region of the sodium pool (Figure 2).

VAPOR BEHAVIOR IN THE SODIUM POOL

The system-wide effect of the gas/vapor species emerging into the sodium pool is to displace sodium into available compressible volume; ie, into the reactor cover gas region. The flowpath includes first the core assemblies as described in the previous section. Upon entering the UIS shroud region the

flow splits; some material flows directly into the REDAN region of the pool by expanding out the gap (~ 7 cm height) that exists between the tops of the core assemblies and the shroud (Figure 2). However, most of the flow is expected to go upward through the lower perforated guide plate. The upper guide plate is not perforated, and the flow is diverted radially through the numerous flow ports on the shroud to mix with the large sodium inventory in the REDAN region. The presence of this structure creates numerous jet-like flows along the path, including the subassembly exits, shroud-to-subassembly gap, perforated guide plate, and the mixing ports. This jet-like flow through the structure causes a dramatic increase in the interfacial area between the flowing vapor and the pool sodium compared to the single, radially symmetric expanding bubble which has been pictured previously. Due to this jet-like flow and due to the relatively small masses of vapor and their relatively slow release rates, it is considered that heat transfer and condensation are likely to occur to an appreciable extent in this system, limiting the gas/vapor expansion process. The results of scoping calculations bearing on this expansion process are presented here.

In the first case, we choose to examine the consequences of the gas/vapor expansion process if no vapor condensation is considered. This provides maximum vapor region growth rates and maximum post-expansion pressure in the system. The released inventory of gas and vapor flows upward through the paths described previously, through the vertical height of the sodium pool, and eventually breaks through the sodium/cover gas interface, entering the cover gas region. In general, the entire inventory of gaseous and volatile species contained core wide (Table 1) would not be entirely released into the system even in the most severe of postulated accidents, owing especially to noncoherence effects. To include this effect in the calculations requires introduction of a release factor which is the ratio of the gaseous and volatile species released to the total inventory of such species. This is termed the disruption release fraction (DRF), expressed by:

$$DRF = X_1 X_2 X_3 \qquad (1)$$

where X_1 = fraction of fuel assemblies undergoing disruption coherently,
X_2 = fraction of pins in fuel assembly undergoing disruption coherently, and

X_3 = fraction of gaseous and volatile species released from failed pins.

Figure 3 shows the pressure in the LPP system as a function of the release fraction, DRF, based upon the isotopic inventories accumulated after the equivalent of one year at full power operation. Also illustrated is the breakdown according to the contributions of the various species present. It can be seen that the maximum quasi-static system pressure for DRF = 1.0 is ~ 7.4 atm, which is well within the pressure capability of the reactor vessel.

In arriving at the pressures in Figure 3, it was considered that the gas/vapor temperature remained at the fuel disruption temperature (~ 1300°C) during passage through the sodium pool to the cover gas region. More realistically, the gas/vapor temperature will be lower, and the vapor will experience condensation as it passes through the sodium. Without resorting to a mechanistic determination of the heat transfer and condensation processes for the present, one can determine the system pressure for any assumed final temperature of the gas/vapor material. This is shown in Figure 4 for the three cases DRF = 0.1, 0.5, and 1.0. The vapor pressure influence of both the bond sodium and the elemental cesium are readily apparant in this illustration. For example, if sufficient heat transfer could be effected during the gas/vapor expansion/migration process to cool the "bubbles" to ~ 800°C, essentially all of the sodium would be condensed and the system pressure would be reduced dramatically. An additional but less dramatic reduction would take place if the bubbles were further cooled to below ~ 700°C due to condensation of the cesium. (Condensation of Se, Rb, and Te would also occur in this range, but would be incidental insofar as reducing pressure due to their small molar inventories). Figure 4 is illustrative of the benefit to be derived from heat transfer to the sodium liquid during the expansion stage. The normal hot pool operating temperature is ~ 500°C. This temperature may increase as a result of the postulated overpower accident, but one feature of the LPP design is the very large inventory of sodium in the hot pool region which causes the heatup to be small. For even the most severe accidents considered, the sodium temperature in this region is not expected to exceed ~ 700°C at disruption onset,[5] and hence there exists a significant potential for vapor condensation.

VAPOR CONDENSATION

To explore the possibility of significant vapor condensation, consider the jet-like flow of sodium vapor emerging from the tops of the core assemblies into the UIS shroud region at ~ 2.8 kg/s as determined in the previous section. The exiting flow is choked. To the authors' knowledge, there exists no data relating to the rates of direct contact condensation of sodium vapor flowing into subcooled sodium which would enable determination of the condensation rate for this system. This process has been extensively investigated for steam and water, however, especially since it has application in the pressure suppression pool in the BWR containment designs. (There is a close analogy between the condensation of steam in the BWR suppression pool and the condensation of sodium vapor in the LPP upper pool). In order to obtain a rough estimate of the condensation rate in the absence of data for the sodium system, we presently utilize the data of Cumo, et al,[8] for the direct contact condensation heat transfer coefficient measured in the steam/water system, and apply their result to the sodium vapor/liquid system. For a sonic steam jet emerging into water, Cumo measured $h_c \simeq 300$ J/s cm^2 C at $\Delta T_{sub} \simeq 100°C$. Utilizing this value of h_c for the sodium system, the interfacial area required to fully condense the sodium vapor jet exiting the top of the core duct is determined from:

$$A_c = \frac{\dot{m}_g \, h_g}{h_c \, \Delta T_{sub}} \qquad (2)$$

where $\dot{m}_g = 2.8$ kg/s·SA, $h_g = 4.6$ MJ/kg for saturated sodium vapor at the exit of the core assembly, $h_c = 300$ J/s cm^2 C, and $\Delta T_{sub} = 280°C$ (pool temp = 700°C). The required condensation area is estimated to be 150 cm^2. This area would be attained in a cylinder above the subassembly (SA) opening of only 6 cm length, about one-half the SA-to-SA pitch. This calculation mearly suggests that if the direct contact condensation coefficients are large in the sodium system, as they are in the steam/water system, that condensation of sodium vapor emerging into the subcooled sodium pool, may occur very rapidly. The value of h_c for the sodium system needs to be addressed through laboratory experiments and related analysis.

CONCLUSIONS AND SIGNIFICANCE

Keeping in mind that the jet-like flow at the SA exit is only the first in a series of such jet-like flow regimes caused by the presence of the UIS, it is reasonable to anticipate that vapor-to-liquid heat transfer, and condensation, are important processes during the upward vapor expansion. It should be mentioned that there is such a large heat sink present in the sodium within the REDAN region of the LPP that the entire available vapor inventory can be condensed with only ~ 1°C temperature rise. The physical picture that emerges differs markedly from previous analyses which involved the rapid growth of a single, large vapor bubble. These scoping calculations suggest that the vapor may condense as rapidly as it enters into the pool (although this remains to be demonstrated). If this physical picture is found to be correct, the implication is that the vapor expansion process is largely eliminated in the IFR system with metal fuel, eliminating with it the capability of performing appreciable work on the system and of transporting radionuclides to the cover gas region where they may be released to containment. We are left with bubbles of noncondensable fission gas rising through the pool to the cover gas region, where they add no more than ~ 1 atm pressure to the system. In fact, a substantial fraction of the noncondensables may be trapped within the UIS shroud beneath the upper guide plate. Fuel and other fission product species would be largely left behind in the core region or retained in the liquid sodium as a result of the condensation process, analogous to the effect of passing through a scrubber system. As long as decay heat is removable from the reactor system, release of radionuclides into the containment would be essentially zero in this physical picture, although the long term leakage-type release of fission gases and perhaps high volatility species needs to be considered further.

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Table 1. Inventory of Gaseous and Volatile Species in Fuel after 1-Year Full Power Operation at 3500 MWt.

Species	Normal Boiling Pt, °C	Inventory, kg	Inventory, kg-moles
Xe	-	195	1.49
Kr	-	18.2	0.22
Br	58	0.11	0.00
I	183	9.2	0.07
Se	685	1.9	0.02
Rb	688	7.8	0.09
Cs	670	123	0.93
Te	900	18.9	0.15
Bond Na*	892	182	7.91

*Contained in Fuel porosity.

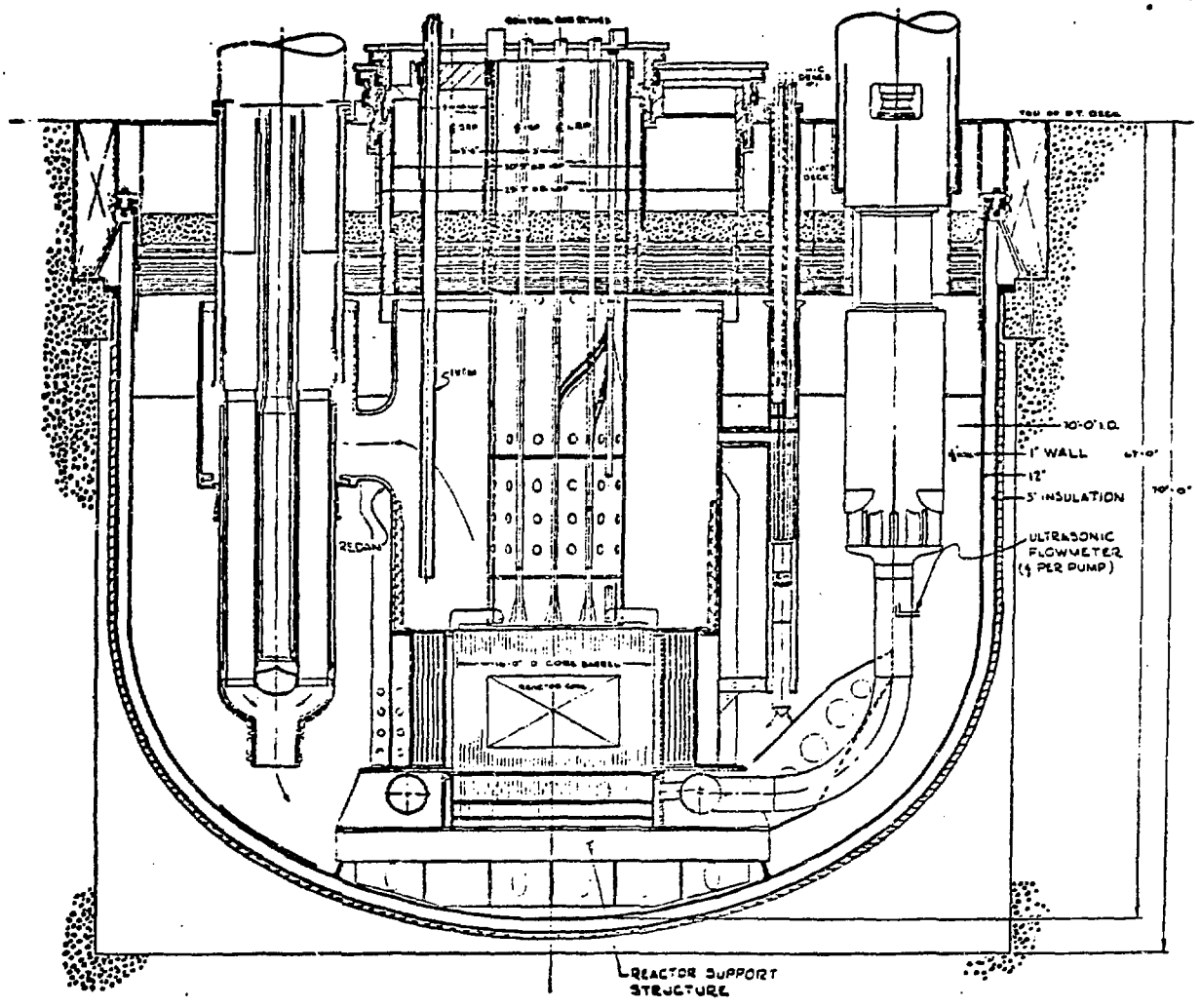

Figure 1. View of Large Pool Plant (LPP), a 3500 MWt Sodium-Cooled, Pool-Type Fast Reactor

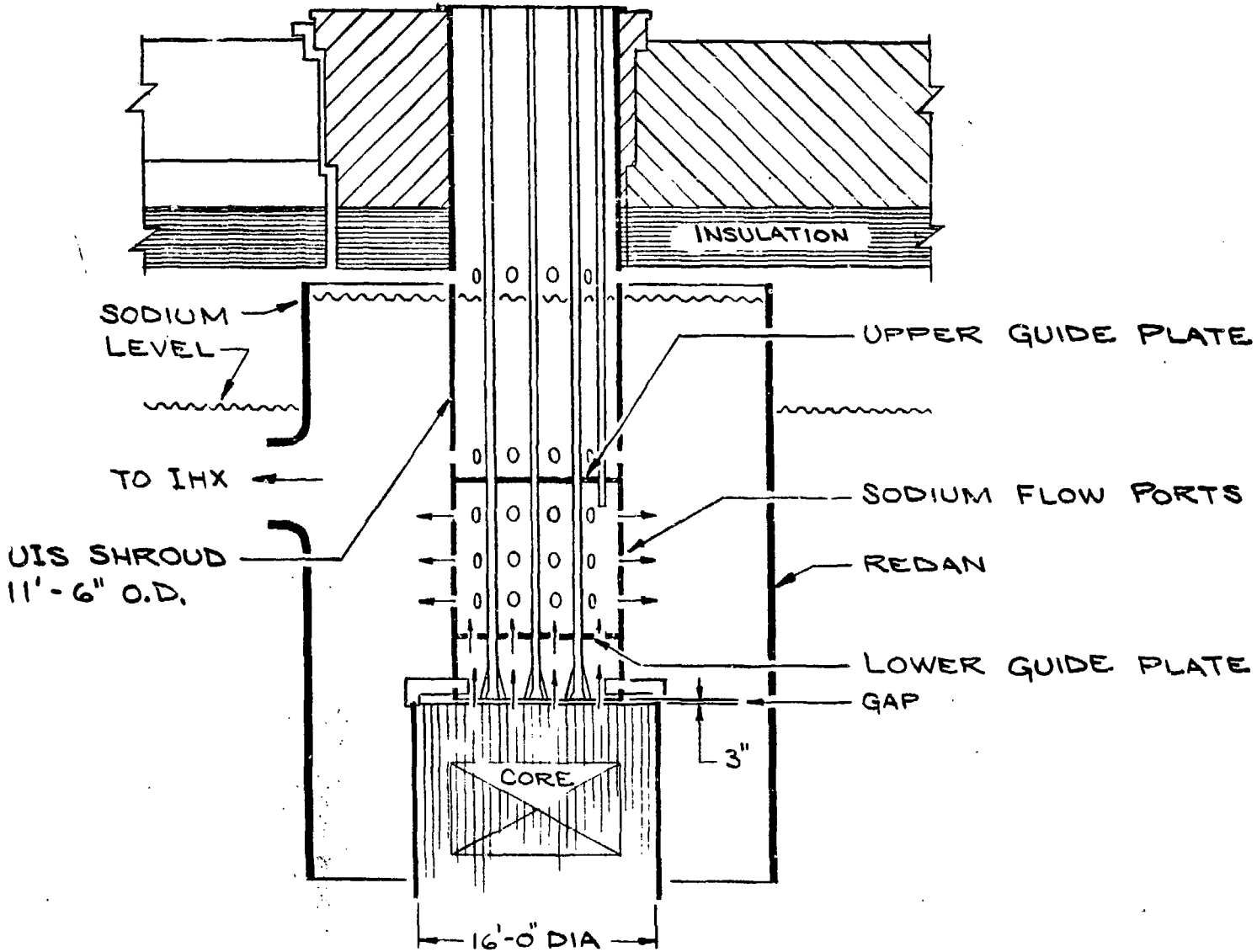

Figure 2. Illustration of Upper Internal Structure (UIS) in LPP.

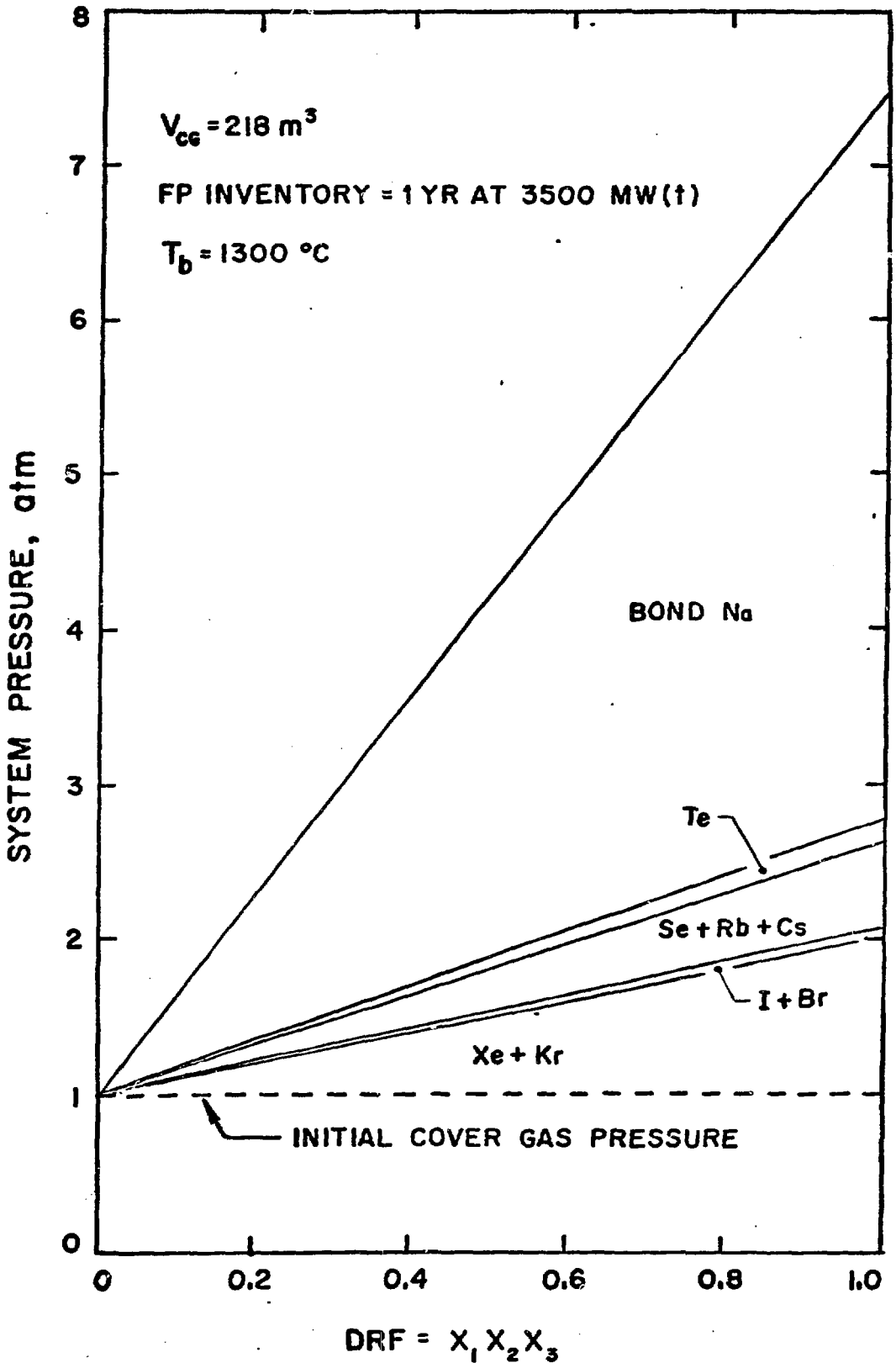

Figure 3. Quasi-static Pressure in LPP vs Fraction of Gaseous and Volatile Species Released without Condensation Attenuation Effect.

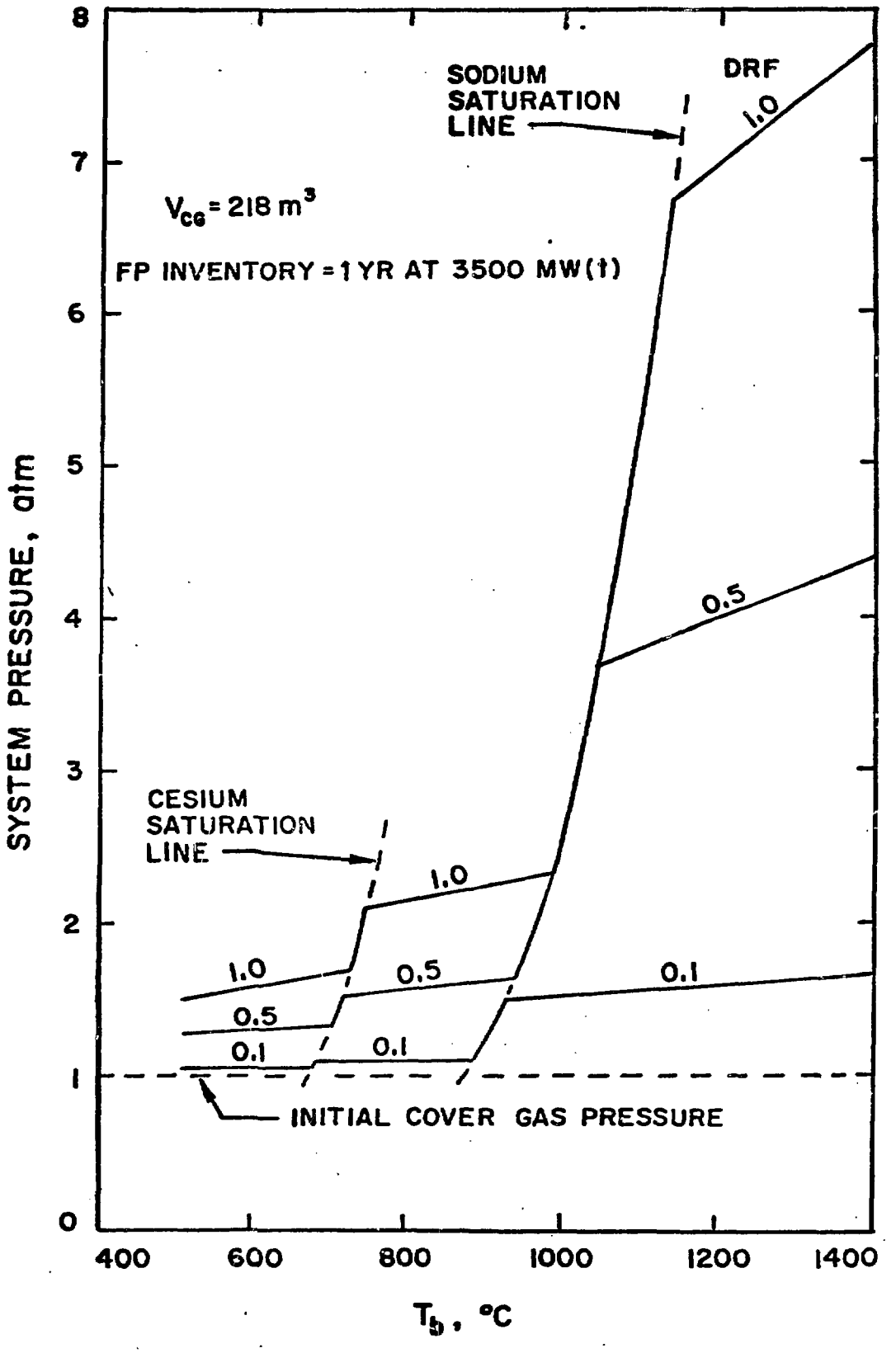

Figure 4. Quasi-static Pressure in LPP for Varying "Bubble" Temperature.