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STEAM EXPLOSIONS IN SLURRY-FED CERAMIC MELTERS

SUMMARY

Attached is a report prepared by Fauske & Associates, with extensive input from SRL. The report assesses the potential for steam explosions, and finds it to be very low. Even if an explosion were to occur, however, the report finds that it would not be large enough to compromise vessel integrity.

BACKGROUND

During the operation of large Slurry Fed Ceramic Melters (SFCM) such as the ones to be used for defense waste processing at SRP and Hanford Wa and for processing commercial waste at West Valley, N.Y., it is possible for a separate $NaCl-Na_2SO_4$ molten salt phase to accumulate on the surface of the glass pool. This creates concern because explosions have occurred in molten glass/water systems, in particular in pulp mills.

Vapor explosions are generally limited to liquid-liquid systems where a hot non-volatile fuel (molten glass-salt) is brought into contact with a colder volatile liquid (water). If the interface temperature exceeds the "spontaneous" nucleation temperature (this condition is met in SFCM systems) such that the volatile liquid is sufficiently fragmented and intermixed with the fuel, a vapor explosion is possible. The required fragmentation and intermixing is greatly retarded in SFCM systems by several factors:

- the firm boiling vapor flux approaches the critical value, indicating the volatile liquid will remain physically separated from the hot liquid preventing significant intermixing. This virtually precludes the onset of explosive interaction.
- glass viscosity (>6 poises) retards fragmentation and mixing.
- the presence of a cold cap would separate the water and molten pool material reducing the required interfacial surface area.
- entrained solids in the slurry and melt could disrupt the coarse fragmentation and intermixing.
- dissolved non-condensable gases tend to make film boiling more stable.
- the presence of a separate salt layer on the melter pool surface could lead to surface interactions which would separate the materials and prevent explosive interactions.
- there is no identifiable trigger to initiate a large steam explosion.
- there is no credible mechanism to produce a steam explosion below the melter pool surface such that slug flow would be established and cause melter damage (even if a slug was formed, its breakup would be very rapid, reducing the likelihood of melter damage).
- the liquid height of water on the melter pool is independent of flowrate and is less than the inventory required for interaciton to seriously challenge the vessel's structural integrity.
- the explosion efficiency is small.

These factors lead to the conclusion that "an in-melter steam explosion would not be of sufficient magnitude to threaten vessel integrity".

STEAM EXPLOSIONS IN SLURRY FED CERAMIC MELTERS

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ABSTRACT

The potential and consequences of a steam explosion in Slurry Fed Ceramic Melters (SFCM) have been assessed. The principles that determine if an interaction is realistically probable within a SFCM are established. Also considered are the mitigating effects due to dissolved, non-condensable gas(es) and suspended solids within the slurry feed, radiation, high glass viscosity, and the existence of a cold cap. An assessment was performed of the maximum available water in film boiling on the melter pool. The maximum potential work, an estimate of the maximum realistic efficiency, and the criteria for determining the

influence of an interaction on the structural integrity of the melter vessel were established.

INTRODUCTION

Plans to immobilize high level defense waste at Savannah River and Hanford and commercial waste at West Valley are based on solidification of the wastes into borosilicate glass. Slurry fed, resistance heated, ceramic melters, such as that schematically illustrated in Figure 1, are the choice for the vitrification process [1]. Glass formers, frit, and/or unreacted chemicals are mixed with the waste, and the resulting slurry is deposited onto the surface of the melter pool. Under abnormal conditions, a separated $NaCl-Na_2SO_4$ molten salt phase can accumulate on the surface of the glass pool. This creates concern because explosions have occurred in molten $NaCl-Na_2SO_4$/water systems [2-8]. The possibility of a molten glass/water interaction must also be considered. However, there have been no reported steam explosions that have damaged the melter vessel in SFCM systems employing the high viscosity (> 20 poise) glasses used in the waste vitrification process [9,10].

An assessment of the melter vessel containment capability must address the possibility of a steam explosion [11-14]. A method of defining and bounding the consequences of a worst case steam explosion in such a system is presented. Even though the possibility of a steam explosion in a SFCM system will be shown to be small, a melter pressurization analysis was developed based on exploding the maximum credible amount of water within the melter. Mitigating effects on the interaction are also considered. While the basic goal is to outline the procedure for analyzing the steam explosion scenario in a SFCM, this approach is also applied to the Defense Waste Processing Facility (DWPF) melter under construction at the Savannah River Plant (SRP) and the West Valley Demonstration Project (WVDP) melter already constructed at West Valley, New York.

VAPOR EXPLOSION MECHANICS

Vapor explosions are generally limited to liquid-liquid systems in which a hot, non-volatile liquid fuel (such as molten glass-salt) is brought into contact with a colder, volatile liquid coolant (such as water). A necessary requirement for an interaction is that the coolant must be rapidly fragmented and intermixed with the fuel to produce new interfacial surface area for heat transfer and vaporization. When the vaporization process is sufficiently rapid to produce a shock wave, the phenomenon is termed a vapor, thermal, or physical explosion, Figure 2.

Vapor Explosion Criterion

The necessary fragmentation and intermixing feature of a vapor explosion requires the interface temperature upon contact between the hot and cold liquids (T_i) to exceed the "spontaneous" nucleation temperature (T_{sn}) of the volatile liquid [15]. Spontaneous nucleation is the process whereby vapor nuclei are formed due to random density fluctuations without external nucleation sites and grow in a liquid against the external pressure due to surface tension and the ambient pressure. Thus, the large scale vapor explosion criterion is:

$$\begin{array}{ll} T_i \overset{-}{>} T_{sn} & \text{explosions are possible} \\ T_i < T_{sn} & \text{explosions not possible} \end{array} \qquad (1)$$

Application of the necessary criterion for a vapor explosion (1) to the molten glass-salt/water system indicates an explosion is possible. However, this criterion only supplies the necessary (not sufficient) condition for a large scale explosion. The required fragmentation and intermixing processes which determine the energetics of the explosion must also be mechanistically addressed.

Premixing of Fuel and Coolant

Intermixing of fuel and coolant would appear possible if the vapor flux in the film boiling regime is well below the hydrodynamically limited, critical heat flux value where the vapor flux exceeds the fluidization velocity [16]. However, if the film boiling vapor flux approaches the critical value and can be maintained, the volatile liquid will remain physically separated from the hot liquid thus preventing significant intermixing. For the molten glass-salt/water system, the film boiling heat flux is nearly the critical value [13]. Hence, significant course fragmentation and intermixing would not be expected in this system [11,13]. Extensive subcooling would be required to enable any significant premixing.

For water added to a molten pool surface potentially containing a mixture of salts as in a SFCM, experiment and experience indicates that surface interactions would separate the materials thus minimizing the probability of a steam explosion. Of the salts potentially found on the melter pool surface in a SFCM (NA_2SO_4, NaCl, etc.), NaCl is the most reactive both thermodynamically and chemically with water. The most energetic, non-externally triggered interactions that have been produced by dropping water in free fall onto molten NaCl have been limited to these interactions that have occurred when only the leading droplets explode upon contact [3,6]. Explosions have not been observed when kilogram amounts of water have been introduced in free fall onto NaCl because the surface interactions limit course fragmentation. The maximum observed efficiency has only been about 14% of the maximum theoretical work [3]. Explosive interactions have ceased above 200 KPa and water subcooling less than approximately 20K [7,13]. Water has also been dropped onto pools of NaCl, Na_2SO_4, and NaCl-Na_2SO_4 mixtures, the latter being with and without an underlying molten glass pool, without producing any significant interaction [8].

Propagation and Fine-Scale Mixing

For systems which have demonstrated propagating vapor explosions, the corresponding propagation velocity is about 100 m/s [17]. Since the fragmentation and intermixing velocity cannot exceed the measured propagation velocity, an estimate of the time required for the postulated fine-scale fragmentation [11] is

$$\tau \sim 3 \ \frac{d}{u} \sqrt{\frac{\rho_F}{\rho_C}} = 3 \left(\frac{0.01 \text{ m}}{100 \text{ m/s}}\right) 2 \sim 10^{-3} \text{ s} \qquad (2)$$

where d is the characteristic particle size resulting from premixing (about 1 cm)

For systems which have demonstrated vapor explosions, the interface contact temperature is generally above the thermodynamic critical temperature while the observed maximum shock pressures are well below the critical pressure [18,19]. The dynamic impact pressure (ρua) resulting from vapor bubble collapse would appear to be the main pressure source available for suppressing the evaporative forces which would tend to separate the materials during the postulated fine scale fragmentation and intermixing process. The time required for intermixing becomes extremely small and is approximately given by d/a_ℓ. The required time to avoid evaporative forces is then approximately (0.01 m/1500 m/s) $\sim 10^{-5}$ s which is much less than the estimated break-up time, approximately 10^{-3} sec, [11]. Consequently, very little fine scale intermixing can occur. The inability to sufficiently intermix the materials during the propagation phase of the explosion may be an explanation for the low energy conversion values ($\leq$ 1%) noted in vapor explosion experiments performed to date [20].

Propagation of Surface Interaction

The depth in the coolant to which mixing occurs in a propagating surface explosion can be estimated assuming hydrodynamic fragmentation [21] as

$$d \sim \frac{1}{3}\left(\frac{\rho_{H_2O}}{\rho_{melt}}\right)^{1/2} u\tau \tag{3}$$

Setting u equal to the propagation velocity (about 100 m/s [21]) and

$$\tau \sim \frac{h}{a_V} \tag{4}$$

where the acoustic propagation velocity in the vapor phase reflects the presence of vapor channels in the liquid layer, the mixing depth becomes approximately 0.5 mm.

As a limiting case, using the foregoing mixing depth in conjunction with the total cross-sectional area of the melter pool indicates the maximum water involved in a surface interaction would be about 1 kg in the DWPF and approximately 0.6 kg in the WVDP. However, the overlying water pool would actually only occupy a maximum of about 14% of the melter pool surface area in the WVDP [13]. Alternatively, it could occupy the entire melter pool area in the DWPF [11]. Consequently, only about 0.1 kg of water could be mixed in the WVDP and approximately 1 kg in the DWPF. Most importantly, the maximum water mass that could hypothetically participate in such an interaction is far less than that required to threaten the structural integrity of the melter vessel of most currently conceived SFCM [11,13].

While a reasonable amount of water could accumulate on top of the melter pool in film boiling, insufficient constraints to allow rapid intermixing would limit the interaction to a relatively small amount of water. The accumulation of additional water on the melter pool is also recognized, however, this would require the presence of a cold cap layer which would separate the water from the molten material. Consequently, the necessary mechanisms required to bring a significant quantity of the lighter, volatile water into intimate contact with the heavier molten pool materials do not prevail.

MITIGATING EFFECTS ON STEAM EXPLOSIONS

Experiment and experience has shown that the high viscosity of borosilicate glass, entrained solids and dissolved gas(es) within the slurry, and radiation from the contained radioactive waste act to mitigate a steam explosion. Although the extent of these mitigating effects is not thoroughly understood, these features decrease the energetics of such an interaction, Table 1. Operational experience of SFCM exceeds 50,000 hours with no reported in-melter violent interaction which has challenged the melter's structural integrity. The important features of each of these mitigating effects are summarized as follows.

Glass Viscosity

The viscosity of borosilicate glasses is considerable in the operating range of a SFCM because the glasses are held near their softening point. The experimental results of Robinson & Fry [9] show the influence of glass viscosity (about 0.2-30 poise, temperature range of 900-1600K) on the possibility of a steam explosion in the molten glass/water system, Figure 3. In the tests without an external trigger, no explosions were produced regardless of the glass viscosity when water was introduced in free fall onto the molten glass surface as in a SFCM. Even when an external trigger was used, no interactions were observed for a glass viscosity exceeding about 6 poise. Since the viscosity-temperature relationships of the borosilicate glasses intended for use in the DWPF and WVDP exceed those used by Robinson & Fry [9], no energetic thermal interaction is expected in these SFCM [13]. Water was also attempted to be "folded" into and under the molten glass, but this did not produce an explosion, no did water injection into the molten glass. In addition, the water and molten glass were more rapidly separated as the water approached saturation conditions. This behavior is consistent with the findings of Krause [8] who observed that even the minor interactions virtually ceased as the water became saturated.

Entrained Solids

Entrained solids within the slurry as well as within the melt can limit (1) course fragmentation and premixing, (2) fine scale fragmentation and intermixing, and (3) the heat transfer surface area. The presence of sufficiently large solids within the water and melt would make the fluids more resistant to course fragmentation and premixing. Therefore, the creation of the necessary pre-explosive state could be more difficult to achieve, Figure 2. In addition, for the water coolant and melt to rapidly fragment and intermix to sustain the propagation of the interaction, the finely dispersed water particles must approach the size (about 100 μm) where conduction is the primary heat transfer mode. However, if the entrained solids are large compared to this final droplet size, the solids could significantly limit this process. Furthermore, entrained solids could decrease the available heat transfer surface area. If the solids occupy a significant fraction of the coolant volume, they may also occupy a substantial fraction of the heat transfer area, and consequently, they could impede the heat transfer to the water coolant.

Dissolved Gases

The basic process involved in initiating a steam explosion is the nucleation of vapor. With the additional partial pressure of a dissolved gas, nucleation of a critical size bubble is easier to achieve, and therefore, much more extensive nucleation would be produced. The enhanced nucleation insures liquid-liquid film boiling and virtually precludes the onset of explosive interaction. Specifically, dissolved CO_2 and/or N_2O in the slurry has been suggested to be able to accomplish the foregoing [10]. Asher et al. [22] indicated that a CO_2 concentration of about 50 ml/kg of water or a N_2O concentration of approximately 60 ml/kg (both about 9% of saturation) could virtually prevent explosions.

External Radiation

Some experiments in which the fuel/coolant system have been irradiated have shown a decreased likelihood of a steam explosion [26]. However, these results are not sufficiently definitive to preclude the possibility of a steam explosion in the design basis evaluation of a SFCM. Other experiments and analyses have been conducted [23,24] which demonstrate that radiation would not substantially influence the initiation of a vapor explosion. With these apparent differences, the conclusion for the design basis evaluation must be that a steam explosion could potentially occur.

EXPLOSION ENERGETICS

The energetics of a steam explosion involves: (1) the maximum interaction pressure, (2) the maximum work yield, (3) the explosion efficiency, and (4) the potential for slug formation and transmission. These topics will be considered briefly as follows.

Maximum Steam Explosion Interaction Pressure

The interaction pressure produced by an inertially limited thermal interaction has an upper limit of about one-half of the thermodynamic critical pressure of the coolant for primarily three reasons. First, the pressure at the beginning of the expansion phase of the explosion, insert in Figure 4, has been observed to be a maximum of about half the thermodynamic critical pressure [7,13]. Secondly, if the maximum developed pressure is viewed as that pressure above which the coolant (water) no longer significantly fragments, the upper limit can be estimated from bubble growth mechanics [11,19]. For H_2O, this occurs at approximately 10 MPa, or about one half the thermodynamic critical pressure (22.09 MPa). Thirdly, the work produced by a freely expanding, atmospheric steam explosion is essentially a maximum for an intermediate pressure of half the critical pressure as will be shown in the next section.

Maximum Work Yield From a Steam Explosion

Mechanical work requires the expansion of a vapor/gas along a thermodynamic path. Consider the path comprised of: (1) a liquid compression along the saturated liquid boundary (approximately a constant volume compression, insert in Figure 4, (2) constant pressure heating from a saturated liquid to vapor, and (3) an expansion along the saturated vapor boundary to the final pressure (nearly an isothermal expansion). The initial state may be either slightly subcooled or saturated liquid, the final state may be saturated or slightly superheated vapor, and the final pressure (P_f) may exceed the initial pressure (P_i).

The available specific work for H_2O determined along this thermodynamic is shown in Figure 4. At an intermediate pressure of half the critical pressure, the available work is nearly a maximum particular for low to moderate final pressures. At these conditions, the maximum available work for the extreme case of the intermediate pressure equaling the critical pressure is only about 8% greater than that corresponding to the intermediate pressure equaling half the critical pressure [14].

Efficiency of a Steam Explosion

Once the fuel and coolant have coarsely intermixed, efficient heat transfer is assumed to only occur until the major expansion of the interaction zone begins, Figure 2. The thermodynamic process representative of this interaction is approximated by the path a-b-g in Figure 5. This path is contrasted to the maximum work path a-b-c-d. The thermodynamic explosion efficiency is then defined as the ratio of the work under the path a-b-g to that under a-b-c-d. This implies that all the coolant involved in the interaction follows the path a-b-g. However, in reality some of the coolant may follow the path a-b-c-d, whereas the remainder experiences very little energy transfer.

For a maximum interaction pressure of half the critical pressure, the steam explosion conversion efficiency is cast as a function of the final pressure in Figure 6. This steam explosion efficiency prediction is at least a factor of two greater than the data. The data shown are for various fuel-coolant pairs and injection nodes and also with and without the use of an external trigger. An external trigger is required to initiate a steam explosion for an initial ambient pressure exceeding about 0.2-1 MPa [7,13,19] and the trigger energy must increase with increasing initial pressure to remain effective.

Potential for Slug Formation and Transmission

The relatively slow energy release rate of a steam explosion requires the presence of a coherent liquid slug above the interaction zone to produce significant damage to surrounding structure. Such energy release occurs over a relatively long period (several milliseconds) because of the comparatively small propagation velocity (about 100 m/s). Most of the energy released in a vapor explosion results from the expanding vapor rather than from shock waves. Hence, the generated vapor must be contained and directed against a coherent liquid slug in order to damage the containing vessel.

Two criteria must be met for efficient slug transmission: (1) the initial slug height (h) must equal or exceed the slug's initial equivalent diameter (d), and (2) the initial slug height must equal or exceed the available length through which it can be driven.

For a postulated surface explosion in a SFCM, this necessary configuration is not present. However, even if in the extreme case the molten pool itself became a liquid slug, maintenance of such a coherent slug can be dismissed based on the Taylor instability phenomenon. A liquid column subjected to an axial acceleration has been shown [30] to break up according to

$$s = K \frac{h^2}{d} \tag{5}$$

For characteristic dimensions of a SFCM, and assuming the entire melter pool is the slug, such a liquid piston would remain intact for only about 1/2 m. However, this is much less than the approximate 1 m necessary for the slug to travel before it would reach the upper surface of the plenum. Hence, little potential exists to damage a melter vessel due to this mechanism.

MAXIMUM AVAILABLE WATER FOR INTERACTION

The maximum credible amount of water available for interaction must be established in such a bounding analysis. Only water is assumed to be introduced onto the melter pool and at the maximum rate consistent with equipment failure and/or operator error. Significant premixing of water into the molten pool has been shown to be unable to occur even with the conservatively large water addition rates. Even with this important observation, a steam explosion involving the maximum plausible amount of water on the pool will be considered in order to bound the worst credible scenario that could occur within the melter. The water on the melter surface will form a quiescent pool in stable film boiling because the molten pool surface temperature is sufficiently high (about 1320K), Figure 7. The influence of a cold cap on the melter pool is also considered.

Film Boiling on Melter Pool

The film boiling condition on the melter pool is supported by direct experimental observations as well as predictions based upon Henry's minimum film boiling correlation [31] as illustrated in Figures 7 and 8. Sodium chloride is employed here to characterize the various salts that may accumulate on the molten pool surface since it is the most reactive material available in the melter [13]. As evident in Figures 7 and 8, the nominal hot liquid surface operating temperature range far exceeds the minimum film boiling criterion for water. Thus, the overlying water above the molten pool would be in film boiling.

Film boiling on the melter pool was also confirmed in small scale experimental studies at the Savannah River Laboratory (SRL) [32]. In these experiments, when water was introduced onto the molten glass surface (> 1370K), a stable overlying water pool was formed. As the water feed was varied, only the pool diameter changed while its thickness remained nearly constant at about 4-6 mm. Film boiling was always observed to prevail.

The pool diameter can be calculated from a standard film boiling analysis as follows [11-13]. At steady operating conditions, the water pool must develop sufficient heat transfer surface area so that the water feed balances the steam exiting the vent system. The film boiling heat transfer rate is assumed to be comprised primarily of radiation and convection, and the heat transfer area is conservatively considered to be only the interfacial area between the lower surface of the water and the top surface of the molten pool. The water pool diameter then becomes

$$D_P{}^2 = \frac{4}{\pi} (\dot{m}_e \, h_{VL}) \left[\epsilon\sigma(T_F{}^4 - T_W{}^4) + h(T_F - T_W)\right]^{-1} \tag{6}$$

The thickness of the water pool can be determined from a force balance between the pressure and surface tension forces acting across the liquid surface around the edge of the assumed circular disk pool as

$$\delta^2 = \frac{2\sigma}{\rho_L g} \tag{7}$$

This model (7) produces a water pool thickness of about 4 mm which agrees with the 4-6 mm thick pools observed in the SRL experiment [32], and the prediction is also independent of the feed rate as was observed. The water mass in the overlying pool is then given by

$$m = \rho_\ell \left(\frac{\pi}{4} D_p{}^2\right) \delta \tag{8}$$

If the overlying liquid pool completely covered the melter pool surface and began to deepen, this would lead to nucleate boiling at the melter pool-water/interface thus creating a stable cooling trend. Consequently, this would lead to the upper pool surface freezing thereby precluding the potential of a large scale steam explosion.

The overlying water pool mass as a function of melter pool surface temperature and water feed rate is shown in Figure 4.3 for the maximum water addition rates characteristic of the DWPF and WVDP systems. These results are conservatively high by approximately a factor of two because heat transfer from the top surface of the water pool was ignored in (6).

Maximum Water on Melter Pool

Since the overlying water pool mass increases with decreasing melter pool surface temperature, the freezing point of NaCl was taken as the condition which maximizes the available water on the melter pool ($\sim$ 12 kg in DWPS and $\sim$ 1 kg in WVDP, Figure 9). Below this temperature, explosive interactions are not possible because the salt is frozen and thus cannot mix with the water coolant. The lower end of the softening temperature range of borosilicate glass occurs just a little above the freezing point of salt making it a slightly less restrictive condition. In this temperature range, the high glass viscosity (> 4000 poise) prevents efficient intermixing thus precluding an explosive interaction. Thus, the criteria employed in this analysis to establish the potential water available for interaction is conservative for two reasons: (1) the heat transfer from the top surface of the water pool was neglected, and (2) the most reactive separated salt that could reside on the molten pool surface (NaCl) was assumed to be able to participate in an interaction even at its freezing point (about 1080K) which is much lower than the typical operating temperature range of the melter (1320 - 1470K).

Influence of Cold Cap

If surface freezing and/or a cold cap should develop on the melter pool surface, no physical limitations of water accumulation in the melter vessel would exist. If the cold cap does not break and remains as a barrier to separate the water from the fuel (molten glass-salt), the possibility of an explosive interaction is eliminated.

If a cold cap did exist on the melter pool, molten salt would not be freely available. Since the formation of a cold cap is a relatively slow process, any pre-existing molten salt layer (density about half that of glass) residing on top of the pool would become chemically bound as part of the cold cap and thus would not be available to interact with water.

MAXIMUM PRESSURIZATION OF THE MELTER VESSEL

A steam explosion occurring in a glass melter could produce a short term, dynamic pressurization of the vessel by a shockwave followed by a longer term, quasi-static pressurization produced by the expanding steam. Each of these two regimes is considered as follows.

Dynamic Pressurization

The dynamic pressure produced by a shock impact onto the melter vessel inner walls is modeled like the shock pressure decay of chemical (TNT) explosives. Experiment has demonstrated that strong shock waves in geometric similar to those of these melter vessels decay as approximately $1/r^2$ [33].

To evaluate the maximum shock pressure at the vessel interior wall, the water considered to participate in the explosion is assumed to initially exist as a saturated vapor at half the critical pressure and in a hemispherical volume above the molten pool. The amount of water is taken as the product of the maximum available water, Figure 9, and the explosion efficiency, Figure 6. The dynamic pressure at the interior walls of the vessel is then determined from a $1/r^2$ decay from the initial radius of the high pressure zone, and this pressure is then doubled as the wave impacts the wall. For the DWPF, this analysis yields about 1.66 MPa which is less than the pressure strength of the vessel (approximately 3.59 MPa [11]). Likewise for the WVDP, the largest dynamic pressure is about 0.32 MPa which is less than the vessel's pressure strength (approximately 0.38 MPa [13]). The actual dynamic pressure incident upon the structural steel boundaries of these melters would be considerably less than at the interior refractory walls because of the nearly 0.3 m additional length and also the compressibility of the interstitial spaces in the refractory liner.

Static Pressurization

The longer term, quasi-static pressurization of the melter plenum is modeled assuming (1) the gases/vapors in the plenum are air and steam, and they behave as a homogeneously mixed, ideal gas, (2) the air and steam are isentropically compressed by the steam explosion and have the same final pressure, and (3) no strain energy is absorbed by the vessel wall.

With the foregoing assumptions, an energy balance on the system equates the steam explosion expansion work to the compressive work done on the plenum gases plus their change in internal energy. This analysis yields a relationship between the final plenum pressure and the water exploded [13]. This relationship is illustrated in Figure 10 for representative conditions within the DWPF and WVDP melter. Once the maximum permissible plenum pressure has been established from a structural evaluation of the melter vessel (DWPF, about 3.59 MPa [11]; WVDP, about 0.38 MPa [13]), the maximum water that can be exploded and yet not exceed this pressure limit can then be determined, Figure 10, for comparison with the maximum available water on the melter pool in film boiling (DWPF, about 12 kg; WVDP, about 0.9 kg), Figure 9.

The results of this analysis, Figure 10, are compared to the maximum available water that can exist in film boiling on the melter pool without a cold cap in the two cases of the DWPF and WVDP melters as follows, Figure 11.

For the DWPF melter, the water required to be exploded to yield the vessel exceeds the maximum available water on the melter pool in the range of observed explosion efficiency, $\leq$ 14% [3]. Furthermore, if film boiling heat transfer were considered off both the top and bottom surfaces of the overlying water pool (6 kg rather than 12 kg of available water, Figure 11), this would preclude the possibility of an in-plenum steam explosion of sufficient magnitude to threaten the melter vessel integrity.

For the WVDP melter, the required water to be exploded to rupture the vessel exceeds the maximum available water on the melter pool in the range of observed explosion efficiencies (less than about 14%), Figure 11. In addition, if film boiling heat transfer were considered off both surfaces of the overlying water pool (0.4 kg rather than 0.9 kg of available water, Figure 11), insufficient water would be available to challenge the vessel integrity even for a perfectly efficient explosion. Thus, an in-melter steam explosion would not be of sufficient magnitude to threaten the vessel integrity.

CONCLUSIONS

Based on the foregoing, the following conclusions are drawn regarding large scale steam explosions in a SFCM.

Primary Results

Explosion efficiency is small. The most frequently observed conversion efficiency of a steam explosion is about 1-3%. However, the maximum efficiency that such an interaction could exhibit and yet not exceed the pressure strength of these SFCM would be about 24-30%. This is approximately twice that demonstrated by the most efficient interaction yet experimentally observed. Consequently, such small observed explosion efficiencies would not result in seriously challenging the melter vessel integrity.

Insufficient water available to damage vessel. The amount of water typically available on the melter pool is less than the inventory required for interaction to seriously challenge the structural integrity of most SFCM for realistic explosion efficiencies.

Mitigation Effects

Cold cap separate water and molten pool. The presence of a cold cap on the melter pool would separate the water and molten pool material. It could permit the accumulation of more water on the melter pool than without its presence. However, the limited exposure between the water and molten pool material could be a more limiting factor on a steam explosion than the amount of available water.

Glass viscosity retards fragmentation and mixing. In the range of operation of a SFCM, the molten borosilicate glass is too viscous to permit significant interpenetration by the slurry. The presence of a cold cap would make this even more difficult. Consequently, the necessary coursely prefragmented and intermixed configuration is difficult to generate.

Entrained solids mitigate interaction. Entrained solids in the slurry and melt could disrupt the course fragmentation and premixing step as well as the fine fragmentation and intermixing stage and limit the available heat transfer surface area and thus mitigate an interaction.

Dissolved, noncondensable gases mitigate interaction. Such gas(es) could make the film boiling layers more stable and thus retard course fragmentation and intermixing hence making a steam explosion more challenging to initiate.

Inherent Phenomenological Safety Features

Surface interactions separate materials. The presence of a separated salt layer on the surface of the melter pool could lead to surface interactions which would separate the materials and hence prevent the escalation to an explosive interaction.

Inadequate external trigger. There is no identifiable external trigger of sufficient magnitude in the melter vessel to initiate a large scale steam explosion even if the coarsely prefragmented and intermixed condition did exist.

Slug formation and transmission unlikely. There is no credible mechanism to produce a steam explosion significantly below the melter pool surface that would create a slug out of part or all of the melter pool. Even in the hypothetical case if a steam explosion were initiated under the entire melter pool, the resulting slug would breakup before impacting the upper head of the melter vessel thus not seriously challenging the vessel structural integrity.

NOMENCLATURE

a - acoustic propagation speed

α - thermal diffusivity

c - specific heat capacity

D - diameter

d - mixing depth

δ - thickness of water pool

ε - thermal diffusivity

FP - freezing point

g - gravitational acceleration (9.81 m/s^2)

h - thickness of liquid layer
- specific enthalpy
- free convection heat transfer coefficient (about 0.3 KW/m^2K)

K - constant in slug breakup relationship (5) (about 2.6 [34])

k - thermal conductivity

$\dot{m}$ - mass flow rate

P - pressure

$\dot{Q}$ - heat transfer rate

R - radius

ρ - density

SP - softening point

s - length through which a slug may be accelerated before it breaks up

σ - surface tension
- Stefan-Boltzmann constant (5.672×10^{-11} $KW/m^2\text{-}K^4$)

T - temperature

τ - time for high pressure mixing following local vapor film collapse

u - explosion propagation velocity
- velocity
- mixing velocity

Subscripts

a - ambient

c - cold liquid
- coolant

co - cutoff

$crit$ - critical

F - fuel

f - final

FB - film boiling

HN - homogeneous nucleation

h - hot liquid

L - saturated liquid

i - interface
- initial

int - intermediate

ℓ - subcooled liquid

p - pool

sat - saturated condition

sn - spontaneous nucleation

V - saturated vapor

VL - saturated vapor minus saturated liquid property value

v - vapor phase

W - water

∞ - infinity

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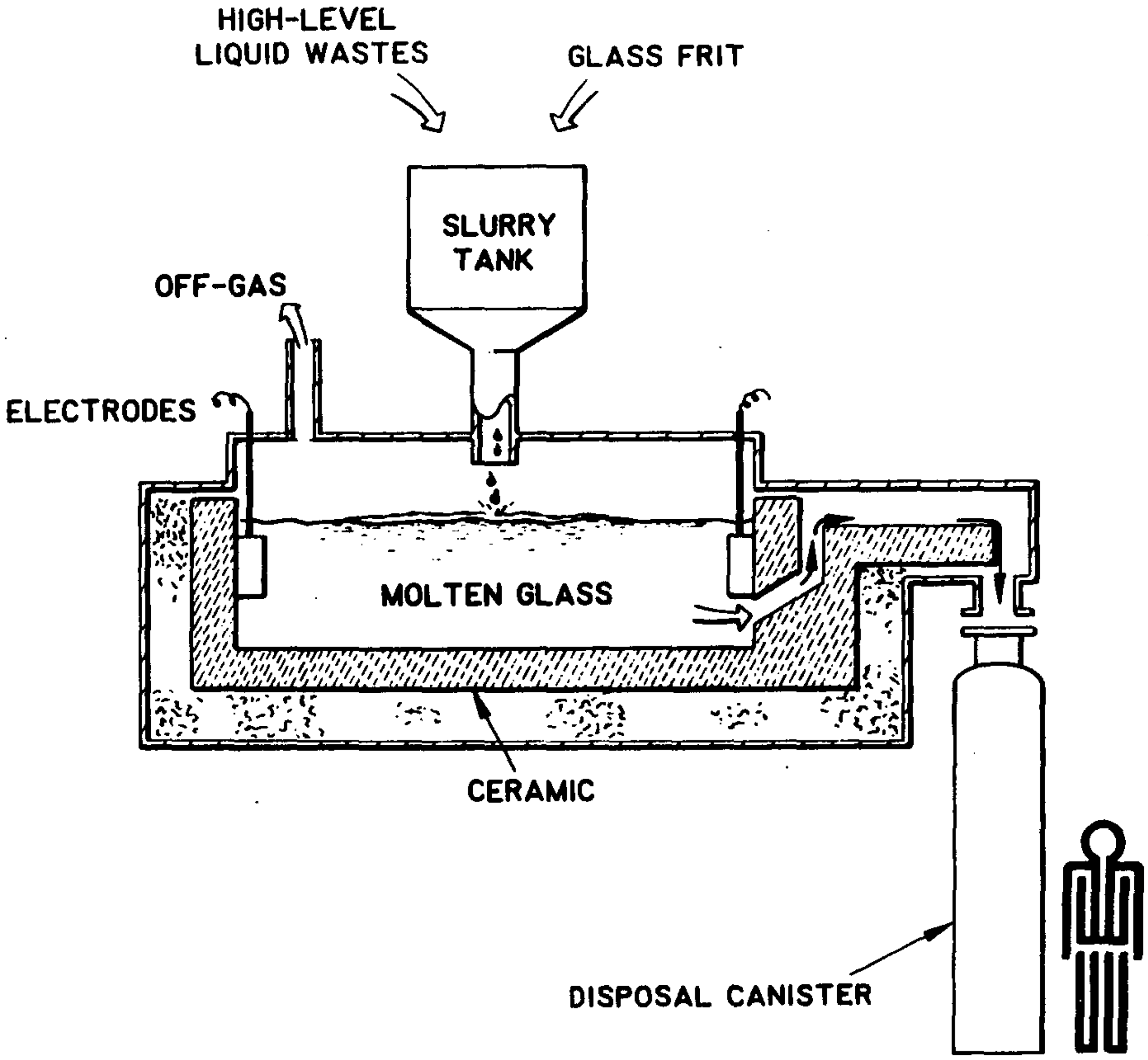

Figure 1 **IMMOBILIZATION OF HIGH-LEVEL WASTE IN GLASS**

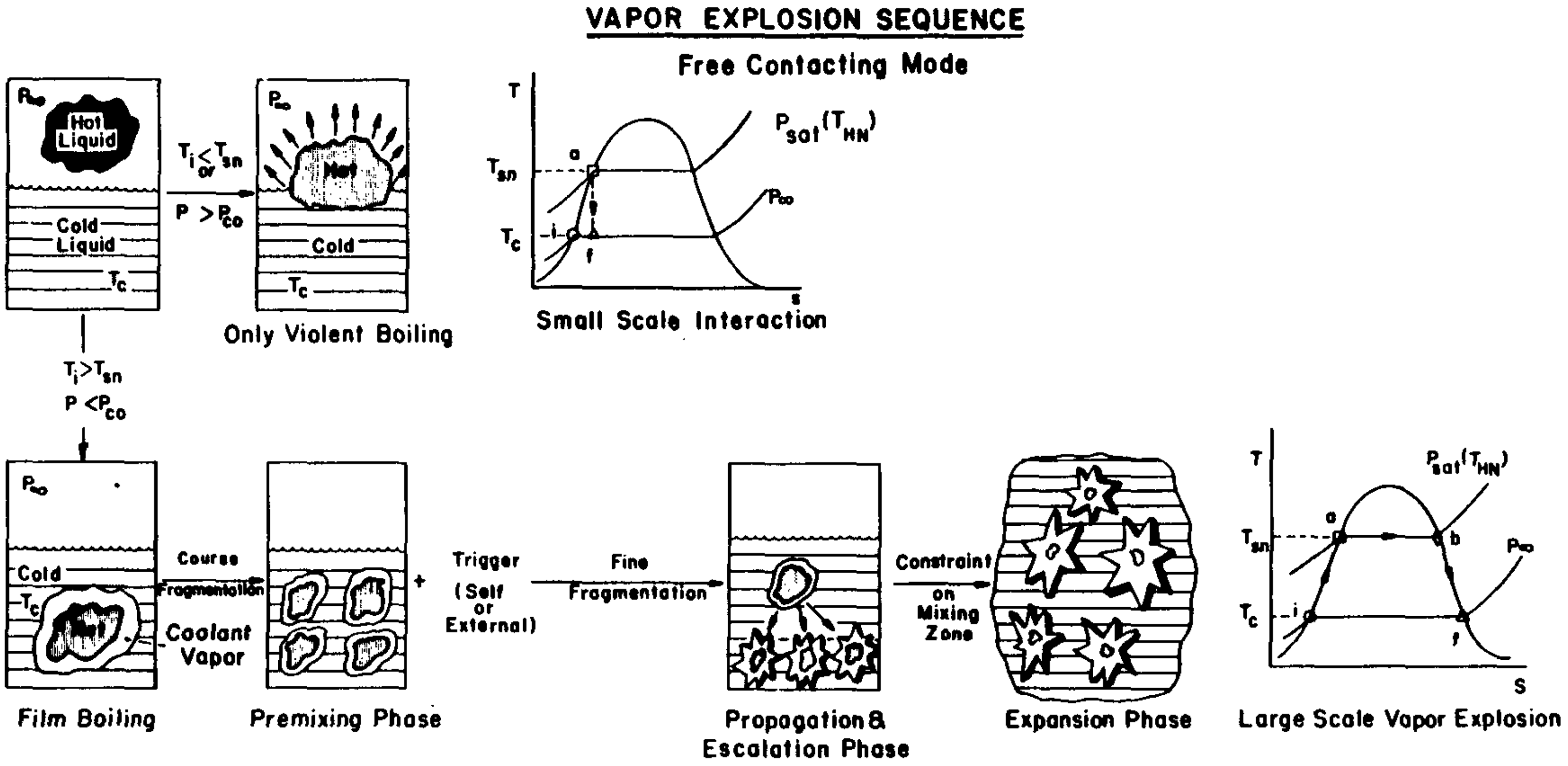

Figure 2 The stages of a vapor (steam) explosion.

Table 1

MITIGATING EFFECTS ON STEAM EXPLOSIONS

Feature	Mitigating Mechanism	Mitigating Impact	Reference
Glass viscosity	Limit course fragmentation & premixing	Significant for viscosity > 6 poise	Robinson & Fry
Entrained solids	Limit course fragmentation & premixing	Significant if particles large enough (> 1 cm dia.)	
	Limit fine scale fragmentation & intermixing	Significant if particles large enough (>100 μm dia.)	
	Limit heat transfer area	Significant if particle volume fraction large enough	
	Enhance nucleation to separate fuel & coolant	Marginal	
Dissolve noncondensable gas(es)	Enhance nucleation to separate fuel & coolant	Good for CO_2 & N_2O	Asher et al. (1976) Postma et al. (1980)
Radiation	Enhance nucleation to separate fuel & coolant	Not definitive to marginal	Claxton (1967) Holtz & Singer (1969) Dietrich (1970) Nutley & Gardner (1980)

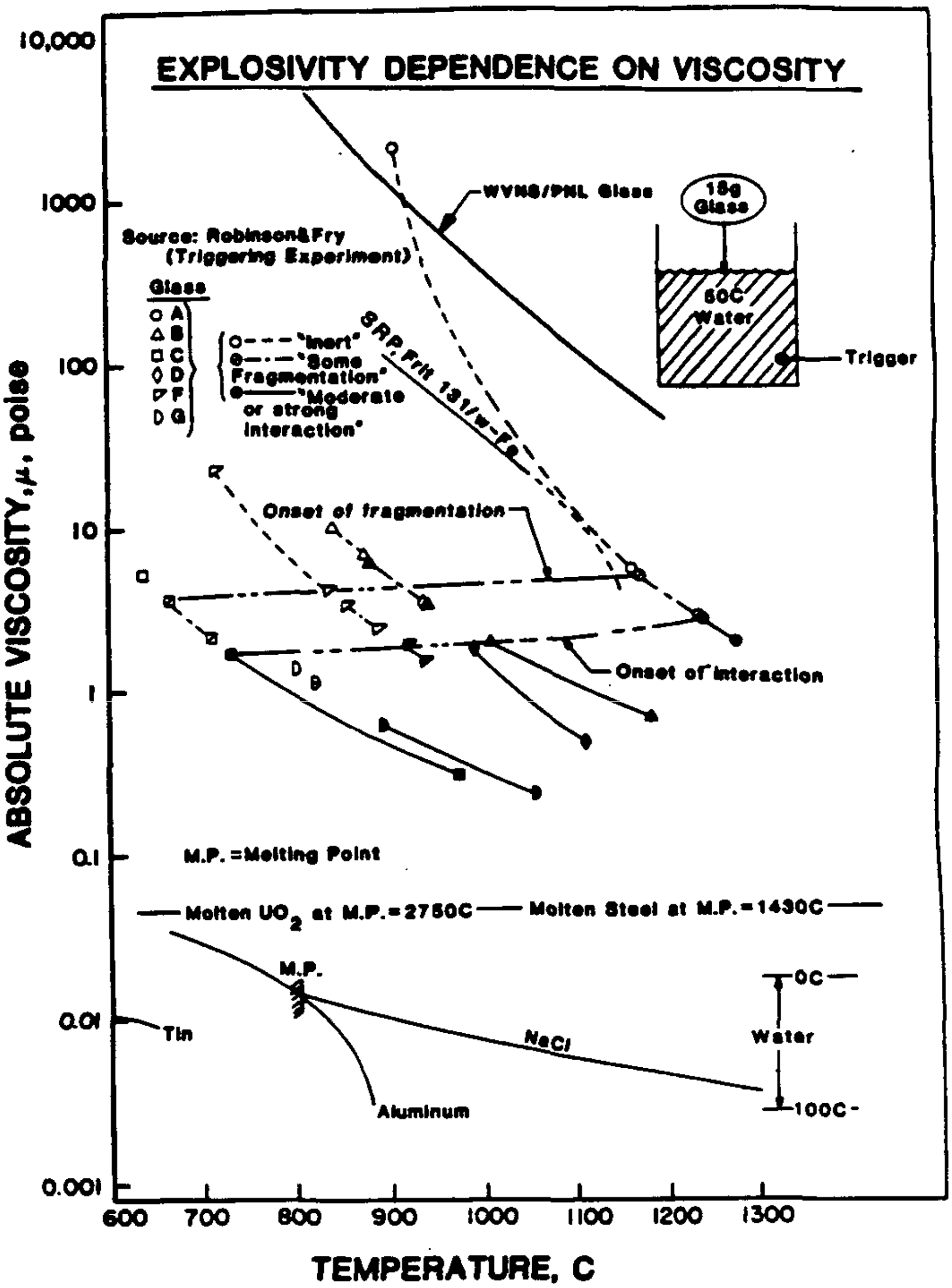

Figure 3 Explosive regime of the glasses used by Robinson & Fry as a function of glass viscosity.

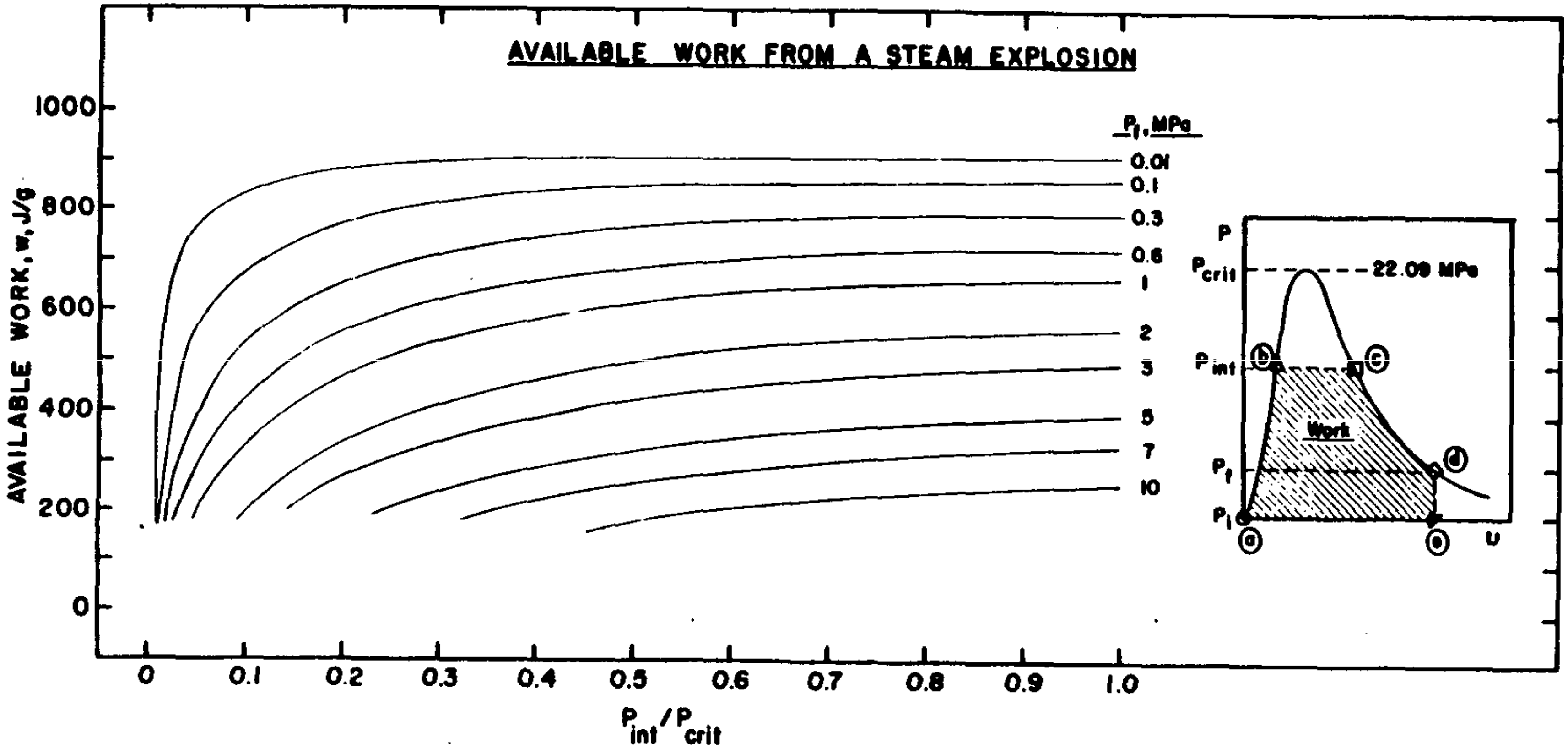

Figure 4 Available work produced by a steam explosion for the indicated interaction path.

$\eta \equiv$ ▨ / ▧

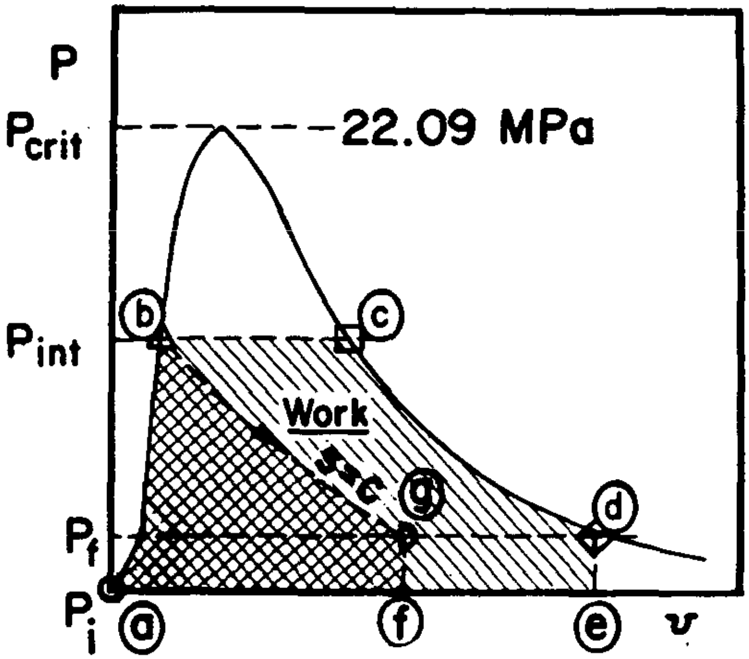

Figure 5 Thermodynamic processes employed in evaluating maximum explosion efficiency.

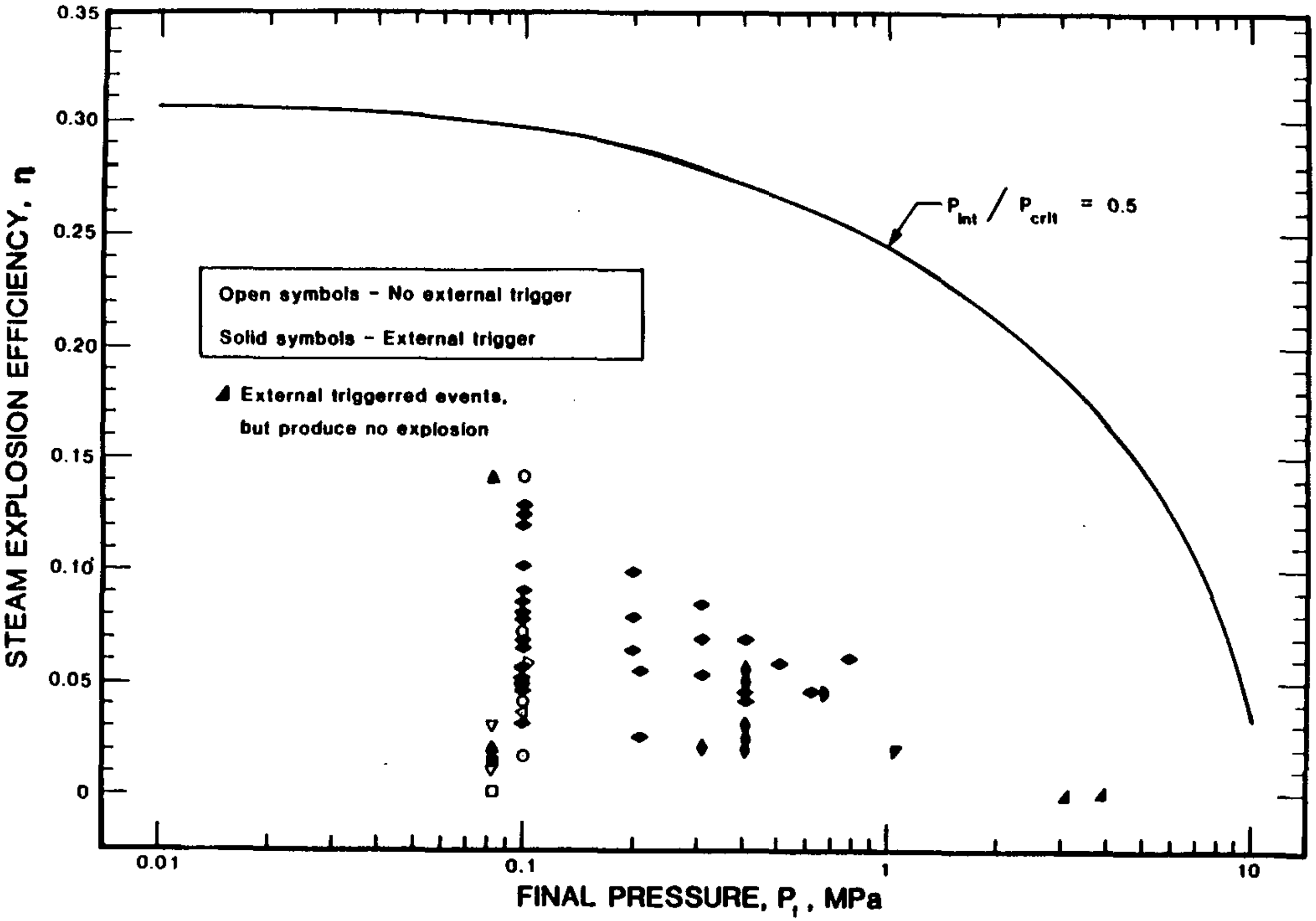

Figure 6 Comparison of the predicted steam explosion efficiency for P_{int}/P_{crit} = 0.5 and the available data [3,7,20,27-29].

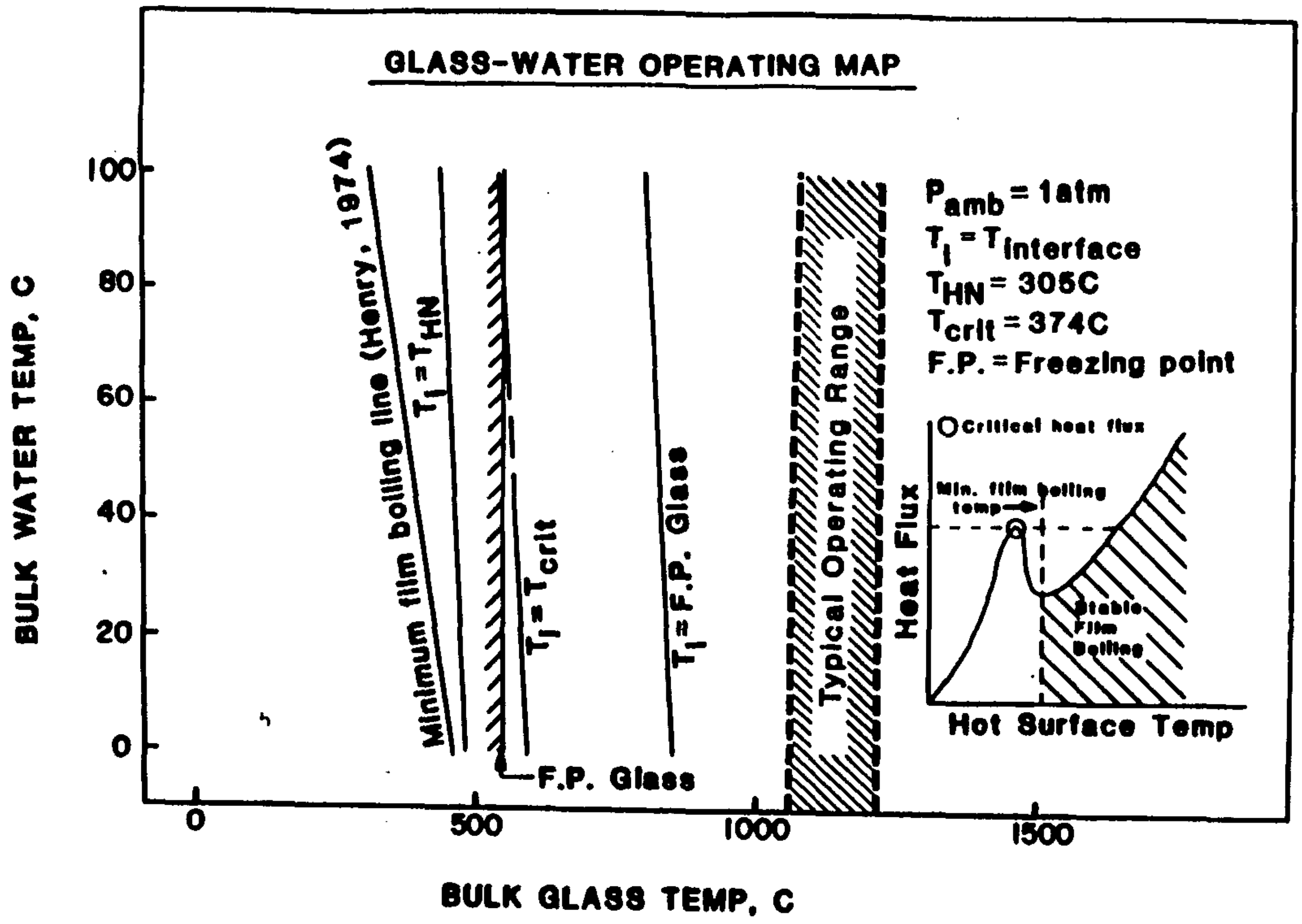

Figure 7 Normal operating regime of the melter with molten glass and water separated by film boiling.

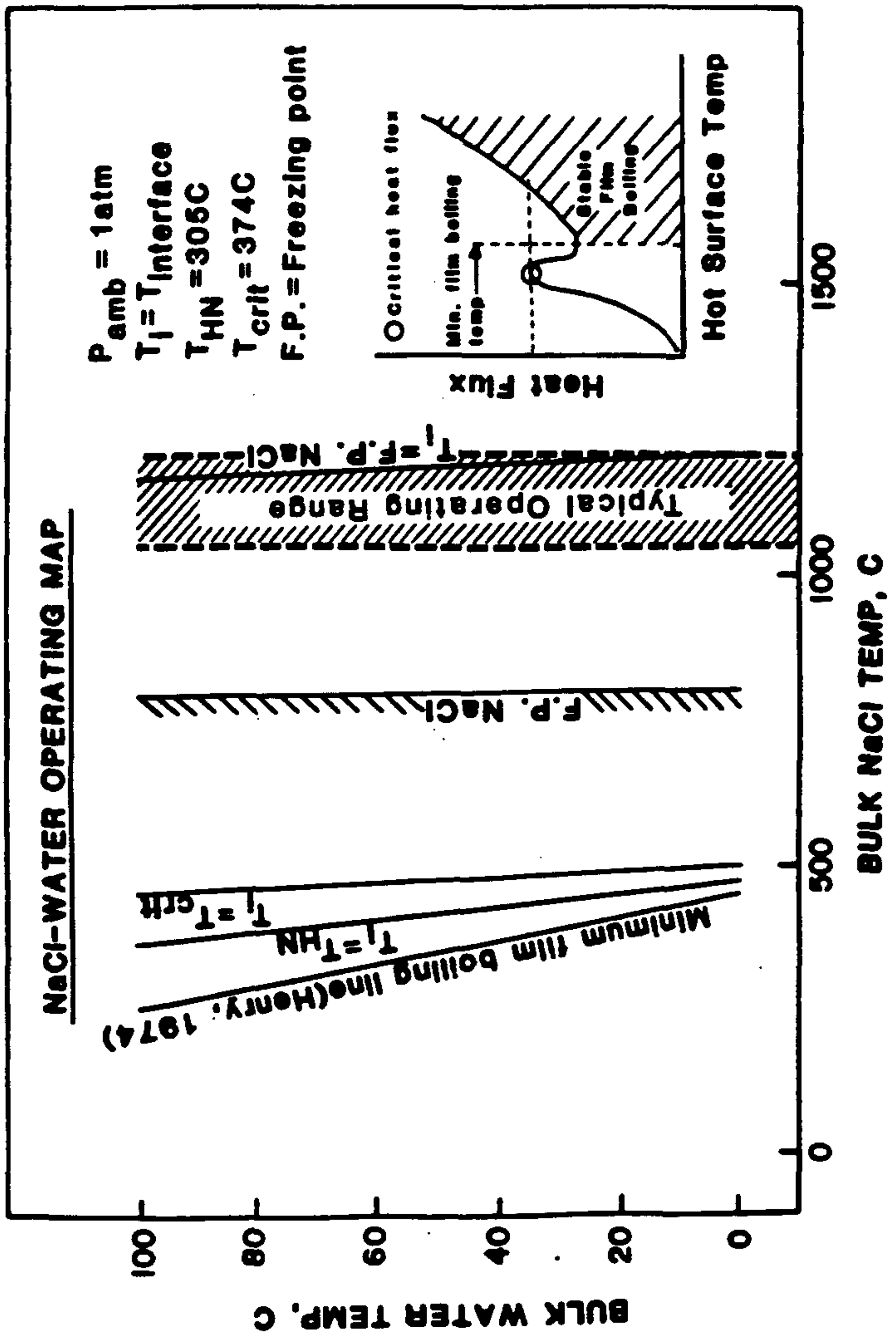

Figure 8 Normal operating regime of the melter with molten salt and water separated by film boiling.

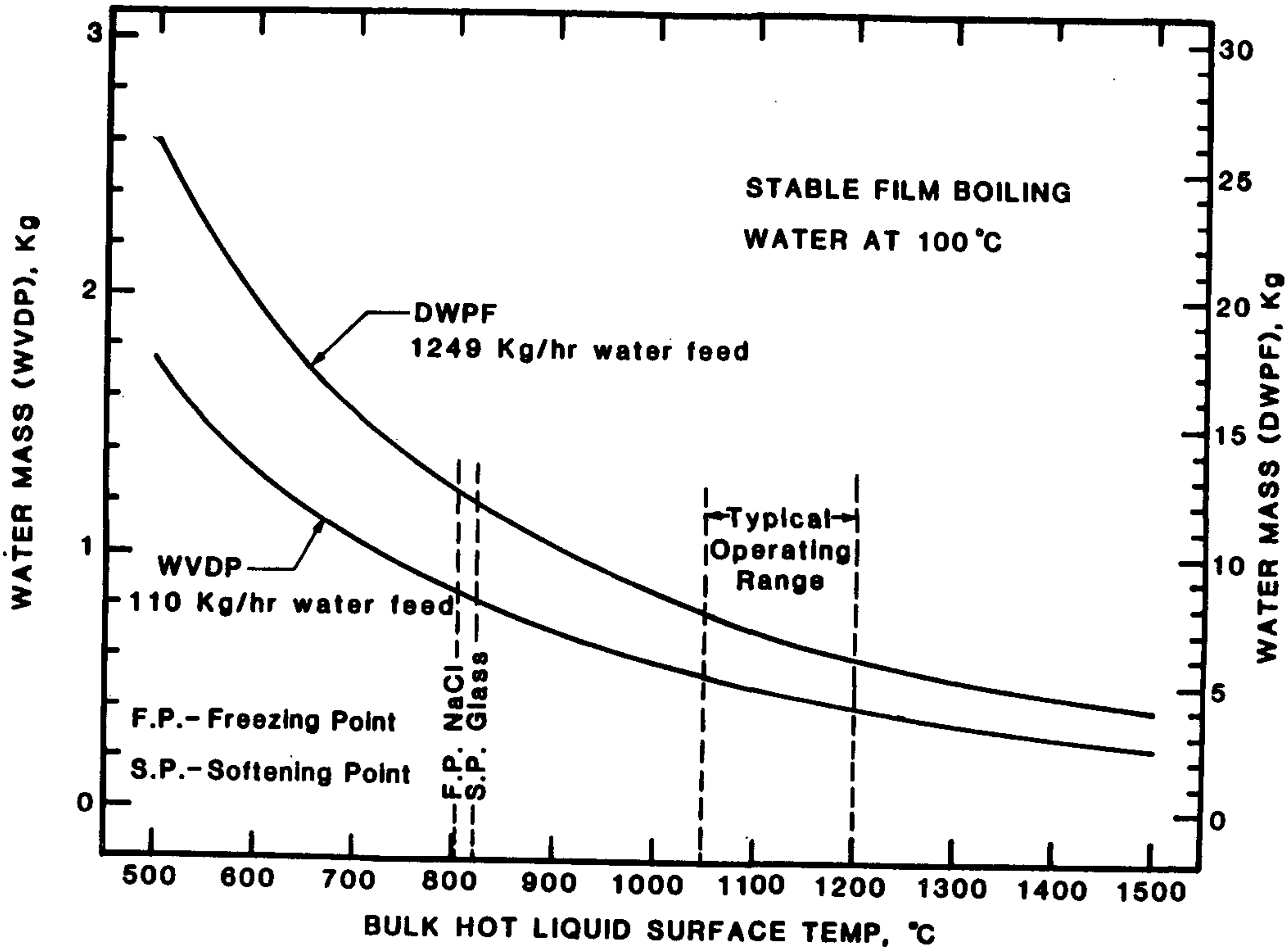

Figure 9 Maximum water mass in stable film boiling on melter pool.

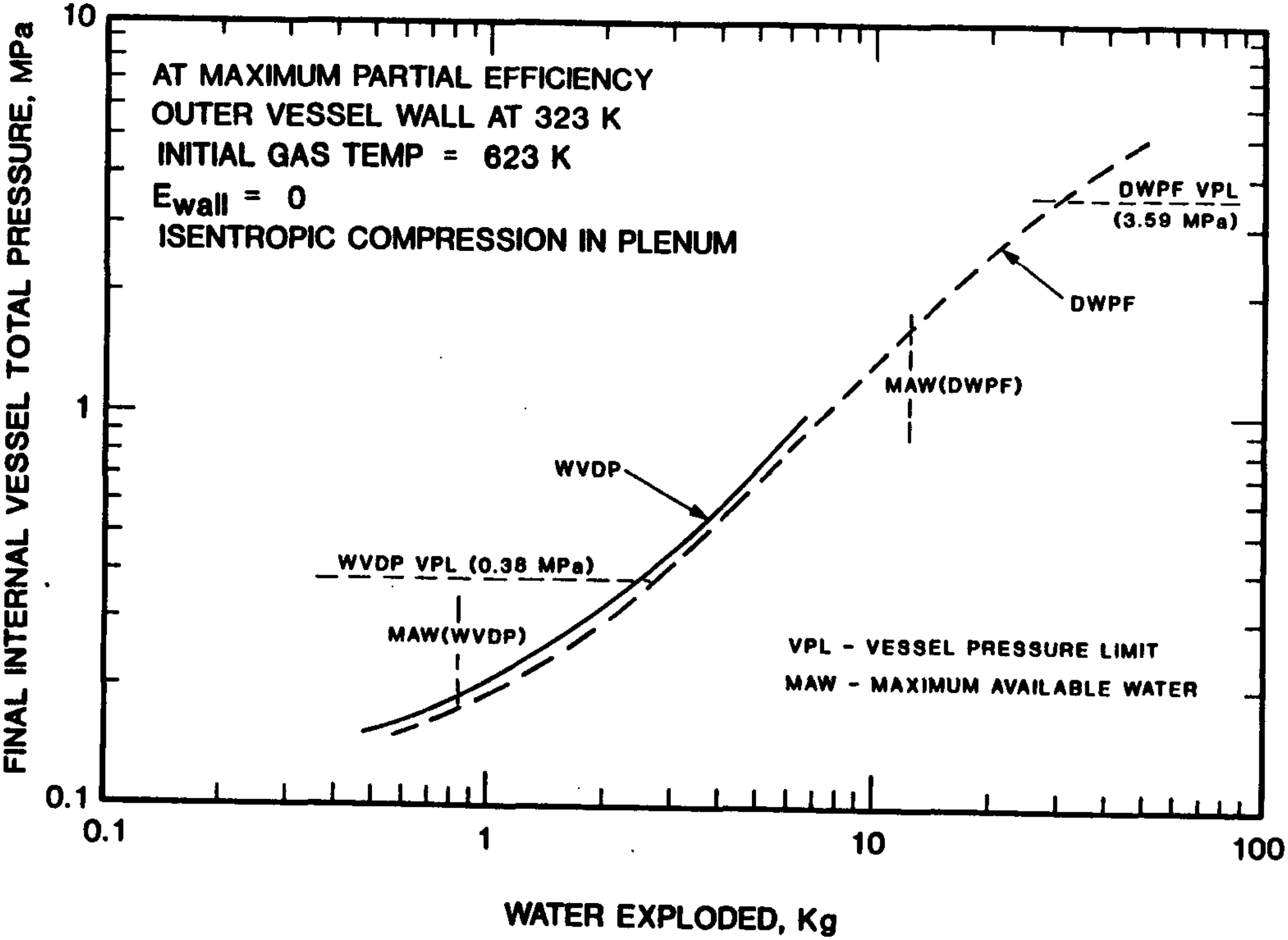

Figure 10 Final internal vessel total pressure as a function of water mass exploded for a maximum efficient interaction.

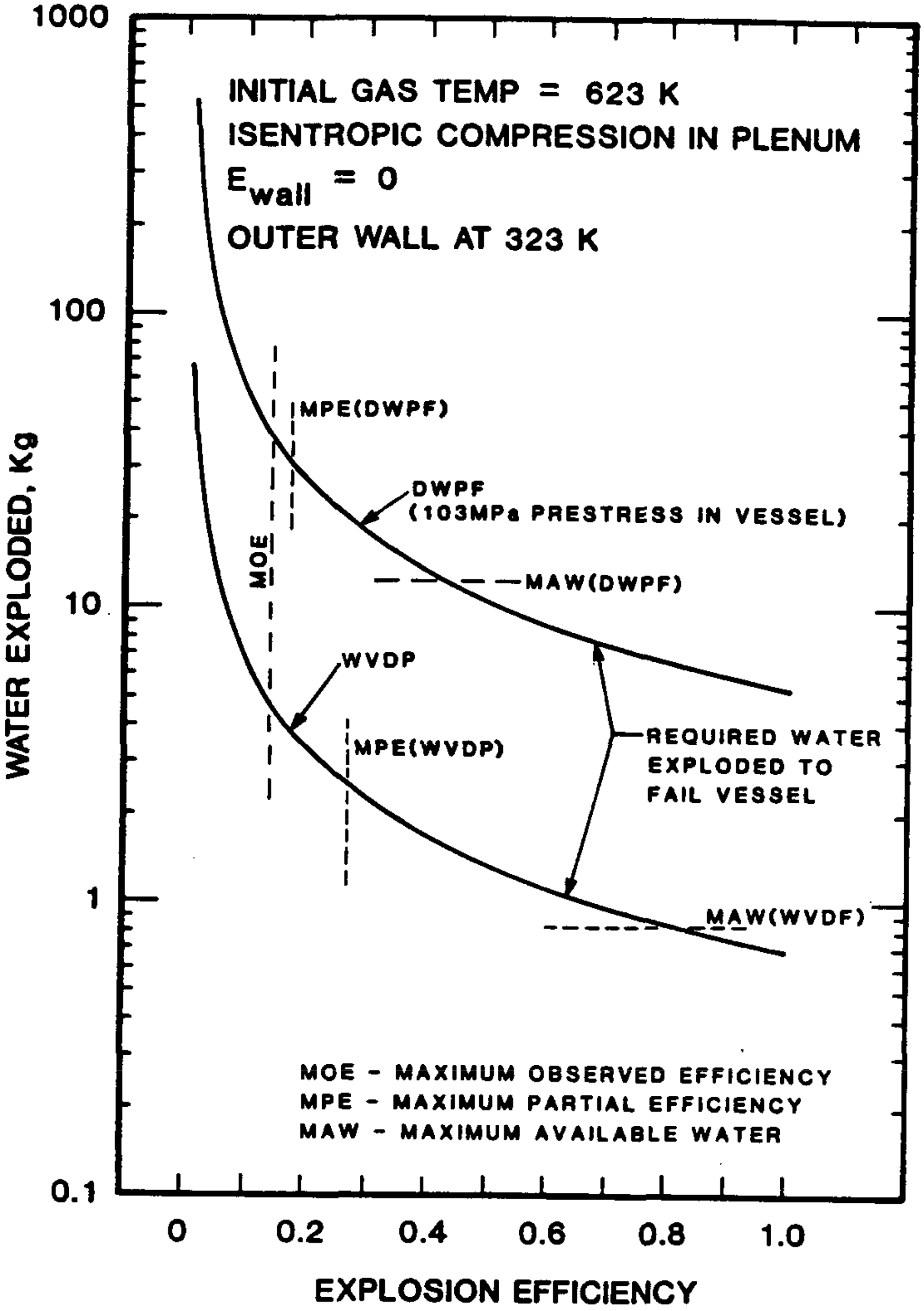

Figure 11 Required water exploded to fail melter vessel.