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AN EXPERIMENTAL STUDY OF SCALING IN CORE MELT/WATER INTERACTIONS

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ABSTRACT

An experimental investigation of the mass scaling of steam explosions involving molten LWR core simulant and water has been undertaken in the Molten Fuel Test Facility at AEE Winfrith. Thermite-generated uranium dioxide/molybdenum melts in quantities of 24 kg were released under the surface of a pool of 1.5 Te of water within a pressure vessel, in large scale replica experiments of earlier work with 0.5 kg melts. Spontaneous and triggered steam explosions were observed with similar characteristics at the different scales. The efficiency of thermal to mechanical energy conversion was low and was unchanged over a range of participating melt mass from 0.03 to 18.0 kg. The efficiency increased with decreasing water subcooling, with a maximum of 4.3% at saturation. In this geometry and at the larger scale, the fraction of participating melt increased with increasing system pressure - from about 13% at 1 bar to 75% at 10 bars. This observation has been attributed to the dispersive effect of coolant vapour production and its importance in the development of melt/coolant mixing.

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INTRODUCTION

Steam explosions involving water and molten core material, which might occur as a consequence of a hypothetical degraded core accident in an LWR, were identified by the Reactor Safety Study (1) as a potential mechanism for the early failure of the Reactor Pressure Vessel and Containment. Subsequent studies (2-4) over a number of years have attempted to determine more realistic estimates of the conditional probability of a steam explosion leading to failure of the Containment. Additionally steam explosions can influence the progression of such accidents by altering the rates at which steam and hydrogen are generated, and by contributing to the dispersion of core debris. Assessment of these phenomena often involves extrapolation from experiments with materials, scales and initial conditions sometimes very different to those appropriate to a reactor accident.

Investigations of the characteristics of Core Melt Coolant Interactions (CMCI) involving reactor materials or other simulant high temperature melts, have been in progress for a number of years (5, 6 for example). This work has established that they proceed through the processes of coarse mixing, triggering, fragmentation and propagation which have been identified as the important mechanisms in coolant vapour explosions. Reactor safety arguments are based on the low efficiency of thermal to mechanical energy conversion observed experimentally, and in particular, the improbability or impossibility of mixing a very large mass of melt (>= 5 Te) with water. However, most of the available data come from experiments involving less than 20 kg of melt, and even so, little is understood of the mechanisms of melt/coolant mixing, or of the scaling of efficiency and mixing to the masses involved at the reactor scale.

This paper reports the results of a series of experiments to investigate the mass scaling of the characteristics of

melt/water interactions, based on replication with 24 kg melts of earlier work carried out at the 0.5 kg scale (5). In any particular experiment at either scale, only some fraction of the melt took part in a steam explosion. Consequently the characteristics of interactions have been observed for participating melt masses from 0.03 to 18.0 kg, corresponding to observed mass scale factors of up to 600. Thermite generated, uranium dioxide-molybdenum melts were employed in a pool mode of contact with water in a closed pressure vessel. This mode of contact was unprototypic to an LWR but has been found to be a reliable and reproducible way to generate CMCI, permitting close control of the initial conditions. It also assisted measurements of interaction yields and pressures, and the recovery of the solidified melt debris. Experiments were carried out with the increased melt mass, to investigate the effects of melt mass scale, water subcooling and initial system pressure on the characteristics of core melt/water interactions.

Experimental Detail

The large scale experiments reported here were the first to be carried out in the new Molten Fuel Test Facility (MFTF) at AEE Winfrith. The central feature of this facility is a large pressure vessel with an internal volume of 1.7 m^{-3} equipped with electrical heating and viewing ports suitable for continuous operation with water to a maximum temperature of 200°C and pressure of 1.6 MPa. Thermite generated melts of uranium dioxide (81%) and molybdenum (19%) in quantities of 24 kg were released from a charge container located centrally under the surface of a pool of 1.5 Te of water, within this vessel. The remaining volume in the vessel, of about 250 litres, was occupied by an argon cover gas. The experiments were designed to replicate, at an overall melt scale factor of 48, earlier work with 0.5 kg melts in the same geometry using water pools of 0.05 m^{-3}. Thus the water scaling factor was only 30, but this was believed to be unimportant since at each

scale the bulk of the water did not come into contact or mix with the melt. The arrangement of the charge container in the MFTF pressure vessel is shown in Figure 1. The distance between the charge container and the debris tray at the bottom of the vessel was 0.7 m.

The thermite charge container was a large steel cylinder, attached at its upper end to a releasing mechanism. This consisted of a casing containing a piston loaded to 10 Te.f by a spring, and retained by two explosive bolts. The piston was connected, by means of a pushrod running coaxially through the charge, to an end cap sealing the lower end of the container. The thermite was ignited in the container with an electrically operated pyrofuze, and the progress of burning monitored automatically via the pressure generated within the container. This typically reached 0.8 MPa on completion following which, after a short delay, a firing signal was sent to the explosive bolts in the release mechanism, freeing the piston and ejecting the lower end cap and melt. The time delay between ignition of the pyrofuze and release of the melt was approximately 4 seconds in the case of 24 kg charges, for which pressures within the charge were observed to rise and level within about the last 300 ms. No measurements were made of the initial melt temperature, but such measurements for the 0.5 kg melts indicated a temperature of 3600 ± 150K. The charge arrangement was essentially an enlarged version of that used in the small scale work with linear dimensions scaled up by a factor of 3.63 - the cube root of the mass scale factor.

Two modes of release were employed: free release in which the melt was released freely into the surrounding water, and restricted release in which the melt was constrained by an open catchpot attached to and ejected with the end cap of the charge container. The catchpot was a thin-walled, stainless steel cylinder, 145 mm deep and internal diameter 274 mm, 10 mm greater than the external diameter of the charge container. On release the catchpot/endcap assembly fell through the water

to the base of the pressure vessel, and tended to contain the melt which was of sufficient volume to have formed a pool about 90 mm deep within the catchpot. Identical modes of release were used in the 0.5 kg scale experiments, in which most were in the restricted mode as this more reliably and reproducibly gave rise to melt/water interactions. The free release mode was dispersive while the restricted mode gave a more constrained and better characterised release. The geometry of the restricted release arrangement for the 24 kg melts is illustrated in Figure 2.

Transient pressures developed within the MFTF pressure vessel were measured by 12 piezoelectric pressure transducers. Three of these were located in the roof to measure cover gas pressures, 6 in the side wall and 3 in the base to measure pressures developed in the water. Two similar transducers monitored pressures in the charge container, and all pressure signals were amplified and recorded on analogue magnetic tape. Two high speed cine-cameras with framing rates of 1500 pps recorded the release of the melt and its interaction with the water.

Experimental Programme

Nine experiments, SUW 01 to 09, were carried out with 24 kg melts, 3 of these were in the free release mode and the remainder in the restricted mode. The initial experimental conditions are summarised in Table 1. Experiment SUW 01 was intended as the 'standard' free release case with experiments SUW 02 and 03 investigating the influence of increased system pressure and reduced cover gas volume on the dispersion of the melt and the characteristics of melt/water interactions. The remaining experiments in the restricted mode were in two groups: SUW 04 to 07 examining the effect of water subcooling, from 80°C to saturation, at a constant system pressure of 0.1 MPa (abs) and SUW 05, 08 and 09 the effect of increasing system pressure from 0.1 MPa (abs) to 1.0 MPa, at a constant

subcooling of 60°C. Additionally, two experiments, SUW 10 and 11 with a melt mass reduced to 8 kg, were carried out in the restricted mode at pressures of 0.1 and 1.0 MPa and 60°C subcooling.

After each experiment the solidified melt debris was dried, then recovered, and the particle size distribution measured by sieving. Water drained from the vessel was sampled, and analysed for the presence of suspended solids by filtration through a 0.45 micron filter, and the particle size distribution of the filtered material was measured from electron micrographs with an IBAS image analyser.

RESULTS

Hydrogen Production

Immediately on contact of the melt with water, in each of the experiments, hydrogen was generated over a timescale of order 100 ms. This effect was seen in the cover gas pressure transients as a step increase in pressure, of about 0.2 to 0.4 MPa, which was also observed as an increase in system pressure measured in the vessel after the experiment. Values of the hydrogen partial pressure for each experiment are shown in Table 2.

Melt Water Interactions

The high speed cine records and vessel pressure transients, showed that the form of the release in both free and restricted release mode experiments was qualitatively closely similar to that observed in the work with 0.5 kg melts. The free mode - as in SUW 01 - tended to be dispersive, but this was reduced by a smaller cover gas volume - SUW 03 - and particularly by an increased system pressure - SUW 02. Restricted mode experiments were less dispersive than those in the free mode, but here also dispersion of the melt

was inhibited at higher system pressures, with most of the melt tending to be confined within the catchpot. Rapid melt/water interactions were observed in each of the experiments, except for SUW 02 and SUW 11, for which only slow vessel pressurisations occurred, corresponding to incoherent boiling over a timescale of about 200 ms. The characteristics of the CMCI were qualitatively similar to those observed in the 0.5 kg work, with spontaneous interactions which generally occurred promptly after release as the catchpot and melt descended through the water, and triggered interactions which were initiated by the impact of the catchpot on the debris tray at the bottom of the vessel. Typical vessel pressure records, corresponding to cover gas and water pressure transients measured in SUW 05, are shown in Figure 3. Interaction yields were calculated as the work done on the vessel cover gas in adiabatic compression to the maximum pressure observed. On this basis yields of interactions occurring in each of the experiments are shown in Table 2. In both free and restricted release experiments, sequences of two or three interactions occurred except in SUW 08, 09 and 10. In these, with the initial system pressure raised to 0.5 and 1.0 MPa (abs) respectively for 24 kg melts or at 0.1 MPa for an 8 kg melt, spontaneous interactions were inhibited and single, relatively energetic triggered events were observed. The cover gas pressure transient for experiment SUW 09, shown in Figure 4 reached a peak value of 17.2 MPa (abs), corresponding to a mechanical yield of 0.88 MJ, which was the highest observed in this series of experiments. In experiment SUW 02 in which no rapid interaction took place, the slow pressurisation of the cover gas corresponded to a work yield of 0.076 MJ.

The overall effect of decreasing the coolant subcooling was to increase the yield of individual spontaneous or triggered interactions. The effect of increasing system pressure was to suppress spontaneous events and to increase the yield of triggered interactions for 24 kg melts, from

about 0.1 MJ at 0.1 MPa to 0.88 MJ at the maximum applied pressure of 1.0 MPa. With 8 kg melts, neither spontaneous nor triggered CMCI were observed for a system pressure of 1.0 MPa. These data are summarised in Table 2.

Melt Debris

After each experiment when the water had been drained from the vessel, the bulk of the solidified debris - from 50 to 90% of the total mass - was recovered from the debris tray. In restricted release experiments, an additional quantity of up to 28% was found in the catchpot, and in most experiments up to 20% of the total debris mass was recovered from the effluent water. In some experiments quite large amounts of debris, from 3 to 43%, were still unaccounted for, and it was subsequently determined that this material was partly held up in inaccessible areas of the drainage system or was carried away and disposed of with the used water. Additionally, sampling of this water showed that it contained a suspension of very fine debris particles with a total mass of from 0.2 to 0.9% of the melt, and a mean diameter, by number, of approximately 1.7 microns and a size range of 0.5 to 13 microns. For debris analysis the material recovered from the debris tray was taken as a sample of the general debris, and it was assumed that the particle size distribution of this material also represented that of the unrecovered debris. Material recovered from the drainage system, excluding that suspended in the water was found to have a size distribution which was very similar to that of the tray debris.

Overall particle size distributions of debris from the free release experiments are shown plotted on log/probability scales in Figure 5. The corresponding data for restricted release experiments are shown in Figure 6, illustrating the effect of water subcooling on the debris, and in Figure 7, the effect of system pressure. Debris distributions were relatively unaffected by the water subcooling, but became

markedly finer with increased system pressure, except for SUW 11, an 8 kg melt at 1.0 MPa, where no interaction occurred and the debris was coarse.

ANALYSIS AND DISCUSSION

Hydrogen Production

In the work with 0.5 kg melts, the quantity of hydrogen generated on melt/water contact was correlated with the volume of the cover gas in the rig vessel (5), which represented the free volume available for expansion of melt and steam into the surrounding water. A figure of 0.72 moles of hydrogen per kg of melt was found for cover volumes of 3.6 litres and about half this value, 0.39 moles/kg for volumes reduced by a factor of 3. On this basis hydrogen generation was judged as an effect controlled by the interfacial area between the melt and water. In this large scale work with 24 kg melts and cover volumes scaled by a factor of 70 rather than the melt scale factor of 48, the average quantity of hydrogen generated was 1.16 ± 0.07 moles per kg of melt for a 250 litre cover volume. The limited data corresponding to cover volumes reduced by a factor of 3 gave 0.33 moles/kg, and for melt mass reduced to 8 kg with a 250 litre cover volume, 2.16 moles/kg.

These data are mostly consistent between the different scales and hydrogen generation is still believed to depend on the area of the melt/water interface. However, there is some evidence in the data that hydrogen partial pressure and coolant temperature may also be important parameters and analysis is continuing.

CMCI - Estimate of Melt Mixing and Efficiency

As in the analysis of the work with 0.5 kg melts (5), the mechanical yields (Yi) of individual interactions were interpreted as the product of a mass of melt (Mi)

participating in the interaction, with an efficiency (E_i) expressed as the mechanical yield per kg of the participating melt. Such that:-

$$Y_i = M_i . E_i$$

This efficiency could be expressed conveniently as a fraction of the thermal energy of unit mass of the melt (1.62 MJ/kg), and in the following analysis, efficiency values were calculated on this basis.

In each experiment, only some fraction of the total melt mass participated in CMCI, and this was interpreted as the amount of melt which had effectively mixed with the water at the time of interaction. The remainder was either too widely dispersed to support an interaction, or was insufficiently mixed. The mass of the participating melt was estimated from the particle size distribution of the melt debris, on the basis that only particles of a diameter of 280 microns or less, contributed significantly to heat transfer on the timescale of the interaction - less than 0.5 ms. This fraction of the melt debris represented the fragmented material and therefore that participating in the interaction. On the basis that the melt that interacted was that which was mixed with water, it also represented an estimate of the mass of melt mixed. In experiments in which more than one interaction was observed, the debris from each interaction could not be distinguished, and net values of amounts of melt mixed and efficiencies were taken.

For each of the experiments with 24 kg and 8 kg melts, the values of the mass mixed and interaction efficiencies are shown in Table 2. For most of the 24 kg experiments, the mass of melt mixed for each interaction was approximately 6% of the total mass. The same proportion in each interaction was found in the work with 0.5 kg melts, demonstrating the accuracy of the replication of these experiments at the larger scale.

CMCI - Effect of Water Subcooling

The efficiency of the interactions involving the 24 kg melts increased approximately linearly with decreasing water subcooling, as shown in Figure 8, with a least squares linear fit to the data having an intercept, at zero subcooling, of 4.1 ± 0.2 % of thermal, and a slope of - 0.020 ± 0.003 % per °C. The corresponding data from the 0.5 kg scale experiments exhibited closely similar values of efficiency and dependence on water subcooling, and this data and a linear fit are also shown in Figure 8, having an intercept of 4.4 ± 0.2 % thermal, and slope of - 0.016 ± 0.003 % per C. At both large and small scales, the data corresponding to interactions with small cover gas volumes showed similar but anomalously low efficiencies, and although these data are shown in Figure 8, they have been excluded from the fits. It is concluded that the efficiencies of CMCI and their dependence on water subcooling, were not significantly different in the two series of experiments at the 24 kg and 0.5 kg scales.

CMCI - Effect of System Pressure

Although for 24 kg melts, the data do not show a dependence of interaction efficiency on system pressure, the yields of interactions in restricted release experiments increased from a net figure of 0.16 MJ at 0.1 MPa to 0.52 MJ at 0.5 MPa and 0.88 MJ at 1.0 MPa (Table 2). This was caused by an increase in the fraction of the mass of melt mixed, from about 13% at 0.1 MPa, to 48% at 0.5MPa and 75% at 1.0MPa. In the case of 8 kg melts, at 0.1 MPa, these showed mixing like that of the 24 kg melts at higher pressures in that spontaneous interactions were inhibited and there was a single triggered event involving 80% of the total mass of melt. The dependence of mixing on pressure is attributed to the different mixing and dispersive effects of the flow of coolant vapour generated by the melt, and the effect of pressure on

the specific volume of this coolant vapour. Effective mixing would require that the melt be distributed in an optimum volume of water. If the actual volume was too small or the melt was dispersed widely in a large volume of water, then the degree of mixing would be relatively ineffective. At low pressures, relatively large volumes of vapour were generated, leading to high flow velocities which tended to disperse the melt in a large volume of water. Such dispersive releases and the decrease in dispersion of the melt at higher system pressures, were observed in the high speed cine films. At the higher pressures, the specific volume of the vapour was reduced, reducing vapour volume generation rates and flow velocities. This reduced dispersion of the melt and assisted the formation of a melt water mixture capable of supporting an interaction.

These processes would be expected to be geometry and scale dependent. The 8 kg melts were released in catchpots of the same size as those used for the 24 kg melts and vapour volume generation and therefore flow rates were proportionately less, which was consistent with the cine film records. Therefore at low pressures, mixing qualitatively like that in the 24 kg melts at higher system pressures would be expected and was observed. In the extreme case of an 8 kg melt at a pressure of 1.0 MPa there was no interaction, possibly because vapour volume generation rates were insufficient to promote significant mixing and consequently no interaction occurred.

The rate of volume generation of coolant vapour and flow out of the catchpot (V') can be represented as a function of the heat flux (Q) per unit area of the melt/water interface, the interfacial area (A), the enthalpy of vaporisation of unit mass of coolant vapour (h) and its specific volume (vs) such that:-

$$V' = Q.A.vs/h$$

The area of the melt/water interface would depend on whether the pool of melt in the catchpot was slumped or boiled up. With the particular catchpot geometry in use, the interfacial area of the fully slumped 8 kg melt ($2.1 \times 10^{-2} m^2$), was approximately 1/3 that of a 24 kg melt ($5.9 \times 10^{-2} m^2$) and this ratio would still apply in the case of fully mixed melts if they were composed of melt particles of the same characteristic length scale. Hence, the quantity vs/h for a 24 kg melt, or vs/3h for an 8 kg melt, is approximately proportional to V'. This parameter is shown in Figure 9, plotted versus the percentage of the melt mass that was mixed in each experiment in the restricted release mode . This demonstrates that ineffective mixing occurred for the dispersive condition of relatively high volume flow rates of coolant vapour (large vs/h) and for very low rates, but that in intermediate conditions, effective mixing could occur.

The role of coolant vapour in the development of melt/water mixing, and the effects of other parameters including geometry and pressure are under further investigation in experiments in the MFTF using a melt pouring mode of contact.

Effects of Melt Mass Scale

The gross characteristics of the melt releases and CMCI were comparable in the 0.5 and 24 kg scale experiments. However, the most striking similarity was in the interaction efficiency referred to the mass of participating melt, and its dependence on the water subcooling, which were not significantly different at the different scales (Figure 8). Since the mass of melt participating in interactions in the 0.5 kg work was typically as low as 0.03 kg, and at the larger scale up to 18.0 kg, a melt scaling factor of up to 600 was appropriate rather than the overall figure of 48. The progression through this range of scales is significant in that it is from a mass of melt with linear dimensions only of the same order as those

characteristic of individual particles in a coarse mixture, to one large enough to form a relatively substantial mixture. It is concluded that the efficiencies of the CMCI were independent of the mass of the participating melt, for the range of mass scales addressed by these experiments.

The pressure dependence of melt mixing, found for the 24 kg melt, was not observed at the 0.5 kg scale. It is likely that the effect is scale and geometry dependent, but development of this analysis will depend on the more detailed study of melt/water mixing processes being undertaken in the MFTF.

CONCLUSION

An experimental investigation has been undertaken of melt mass scaling in CMCI, with 24 kg uranium dioxide/molybdenum melts released into a pool of 1.5 Te of water within a pressure vessel, replicating earlier work on a 0.5 kg melt scale. The characteristics of melt/water interactions were studied as a function of water-subcooling and system pressure. The principal results were:-

1. Spontaneous and triggered melt/water interactions were observed with the 24 kg melts, with characteristics similar to those occurring in the small scale work, but with mechanical yields in the range of 0.02 to 0.88 MJ.

2. The efficiency of thermal to mechanical energy conversion, referred to the mass of melt participating in the interaction, increased with decreasing water sub-cooling with a maximum at saturation, of 4.3% of the thermal energy of the melt. The efficiency was not a function of the melt mass scale and was unchanged over a range of participating melt mass from 0.01 to 18.0 kg.

3. For the 24 kg melts, the fraction of the melt participa-

ting in melt/water interactions increased with increasing system pressure, from about 13% at 0.1 MPa (abs) to 75% at 1.0 MPa. This was interpreted as a mixing effect which was scale and geometry dependent, and was not observed in the work with 0.5 kg melts. In a small number of experiments with 8 kg melts, but otherwise in the 24 kg melt geometry, similarly enhanced mixing was observed at a pressure of 0.1 MPa, but was apparently inhibited at 1.0 MPa. These mixing effects were attributed to the influence of coolant vapour generation, and the effect of pressure on coolant vapour properties.

Melt water mixing processes and the effects of the system conditions of geometry, pressure and coolant subcooling are being investigated in further experiments, in a melt pouring mode of contact.

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TABLE 1: INITIAL EXPERIMENTAL CONDITIONS IN THE SUW SERIES

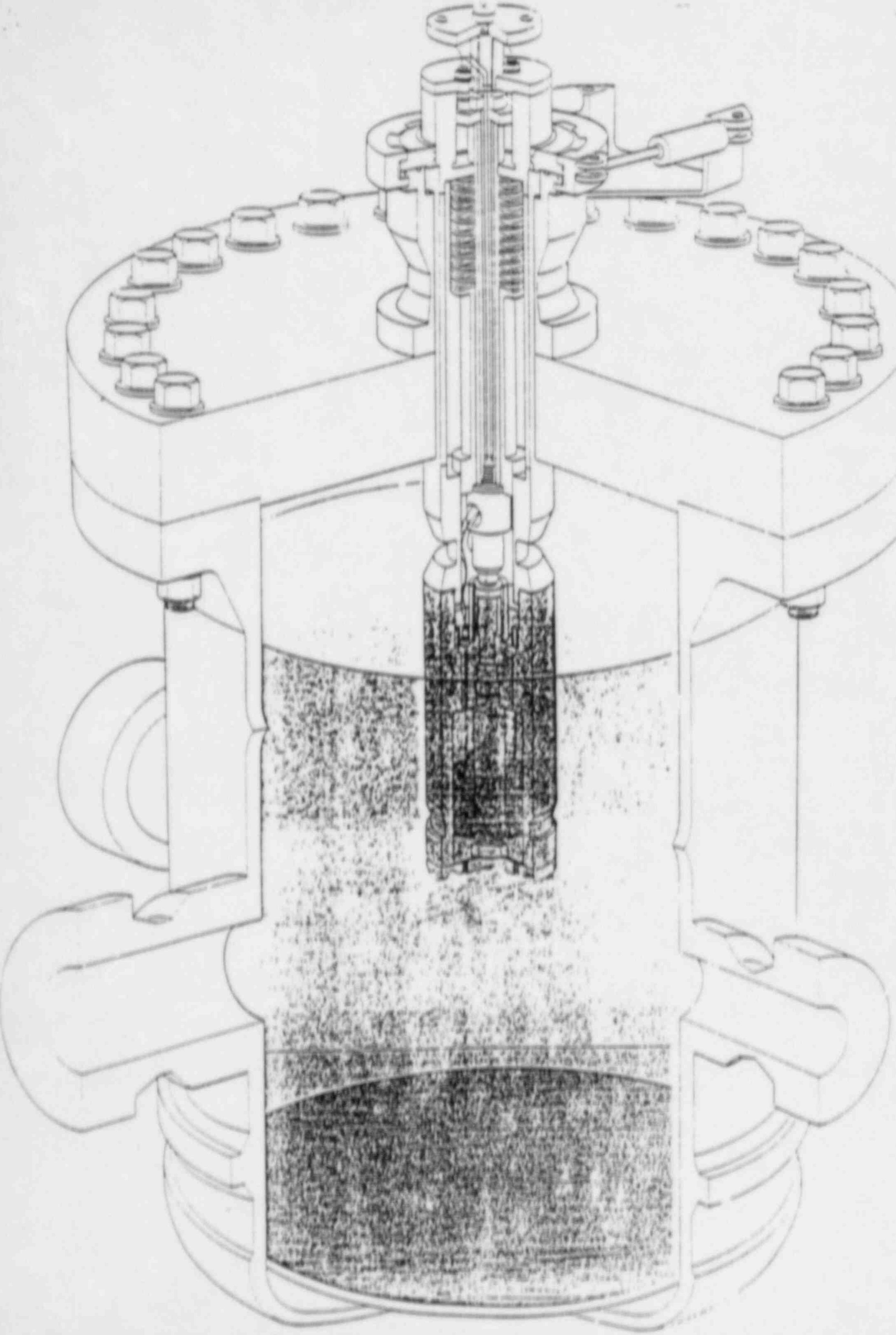
Exp	Release Type	Melt Mass (kg)	Cover Vol (Litres)	Absolute Pressure (MPa)	Water Subcooling (deg C)
SUW 01	Free	24	250	0.1	78
SUW 02	Free	24	250	0.4	87
SUW 03	Free	24	85	0.1	80
SUW 04	Restr'd	24	250	0.1	80
SUW 05	Restr'd	24	252	0.1	61
SUW 06	Restr'd	24	271	0.1	31
SUW 07	Restr'd	24	251	0.1	0
SUW 08	Restr'd	24	259	0.5	60
SUW 09	Restr'd	24	250	1.0	60
SUW 10	Restr'd	8	250	0.1	60
SUW 11	Restr'd	8	250	1.0	60

TABLE 2: EXPERIMENTAL RESULTS OF SUW SERIES

Exp	Hydrogen Partial Pressure	No of CMCI	Total Yield (MJ)	Fraction of melt mixed (%)	Efficiency (% of thermal)
SUW 01	0.23	3	0.223	20.4	2.8
SUW 02	0.27	0	0.076(i)	3.9	-
SUW 03	0.23	2	0.077	12.5	1.6
SUW 04	0.23	3	0.175	19.9	2.3
SUW 05	0.25	2	0.162	13.0	3.2
SUW 06	0.28	2	0.160	13.1	3.1
SUW 07	0.42	3	0.225	13.5	4.3
SUW 08	0.40	1	0.521	48.2	2.8
SUW 09	(ii)	1	0.884	75.0	3.0
SUW 10	0.18	1	0.118	80.0	1.1
SUW 11	(ii)	0	0.0	9.0	-

Notes: (i) Slow pressurisation from incoherent coolant boiling.

(ii) Measurement not available.



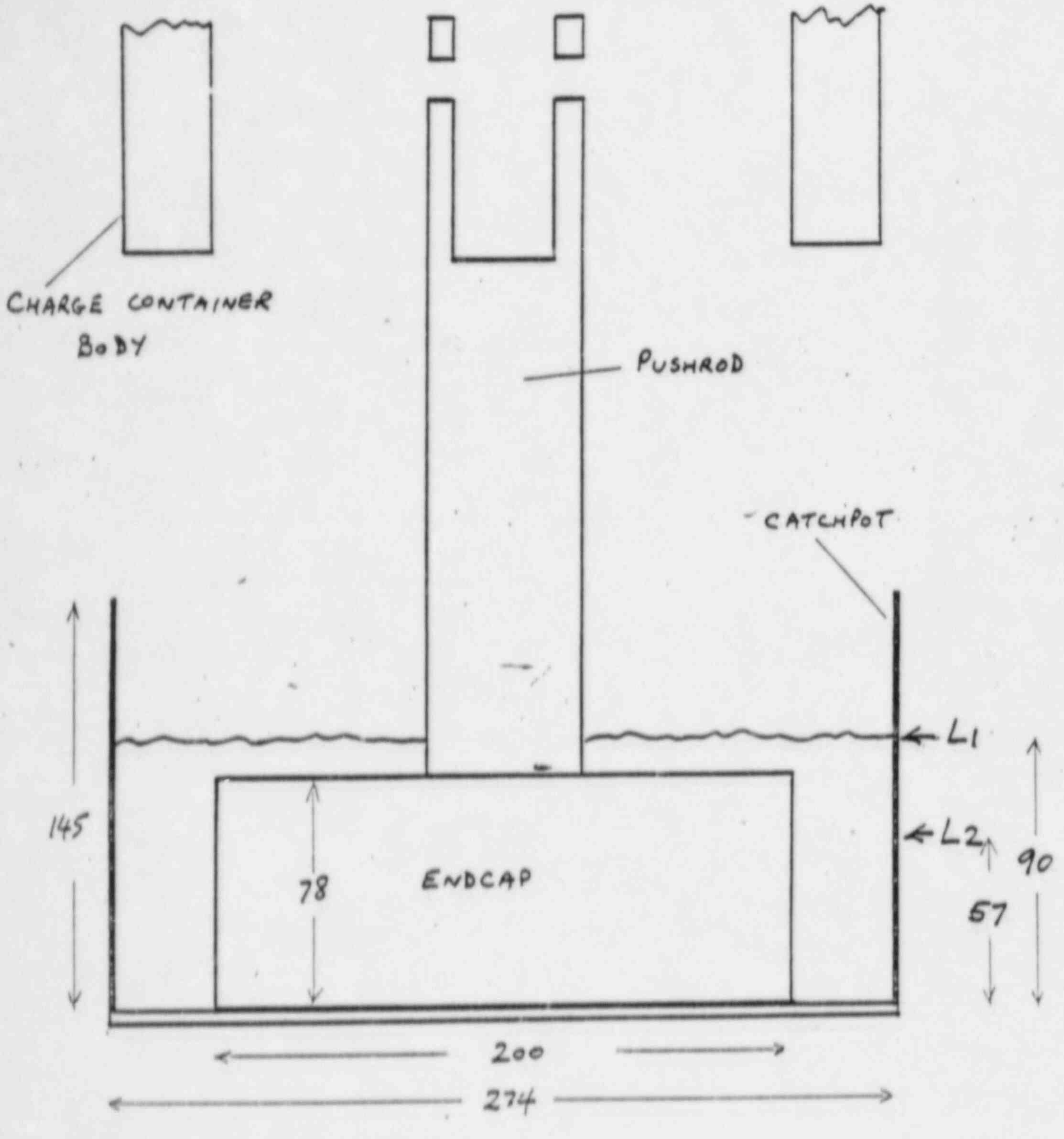

CHARGE CONTAINER BODY
PUSHROD
CATCHPOT
L1
L2
145
78
ENDCAP
90
57
200
274

Fig 2

EXPERIMENT FILE NO. 1 UW05 007 290983 01 1 06 009 003

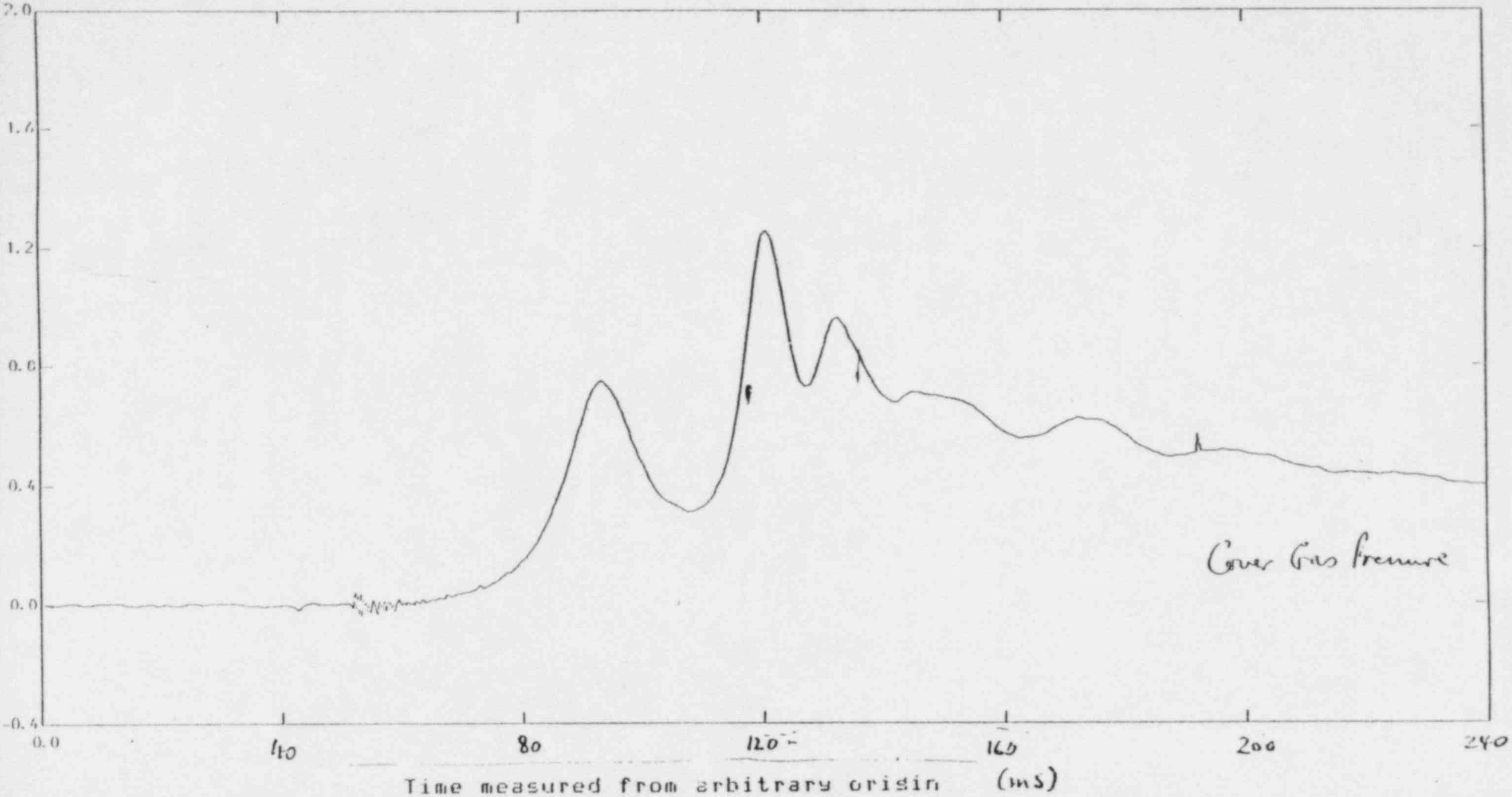


Figure 3". Cover gas pressure transient
- spontaneous and triggered interactions in
experiment SUW 05.

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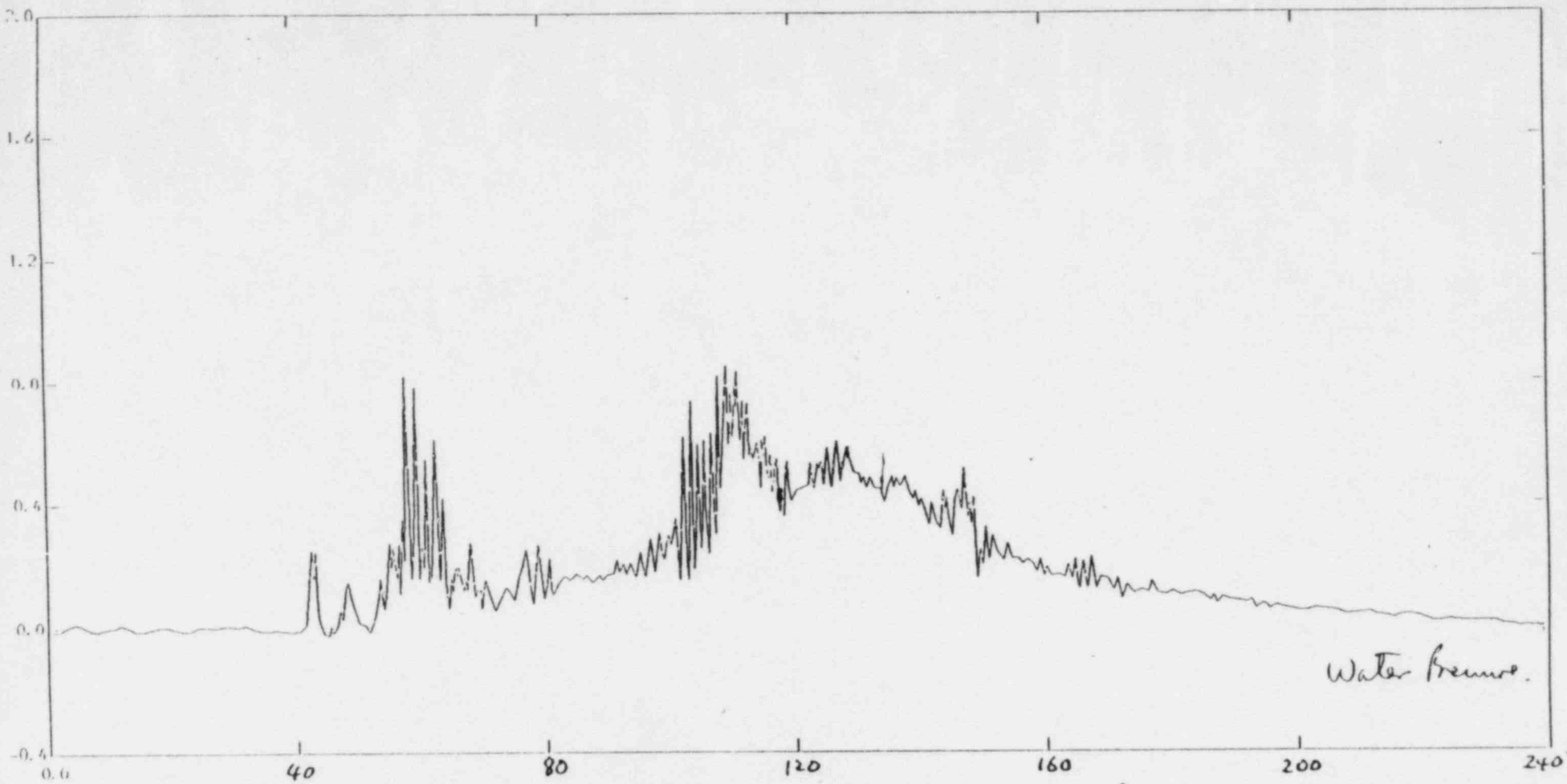

Figure 3b.
Pressure transient - spontaneous and triggered water interactions in experiment SUW 05.

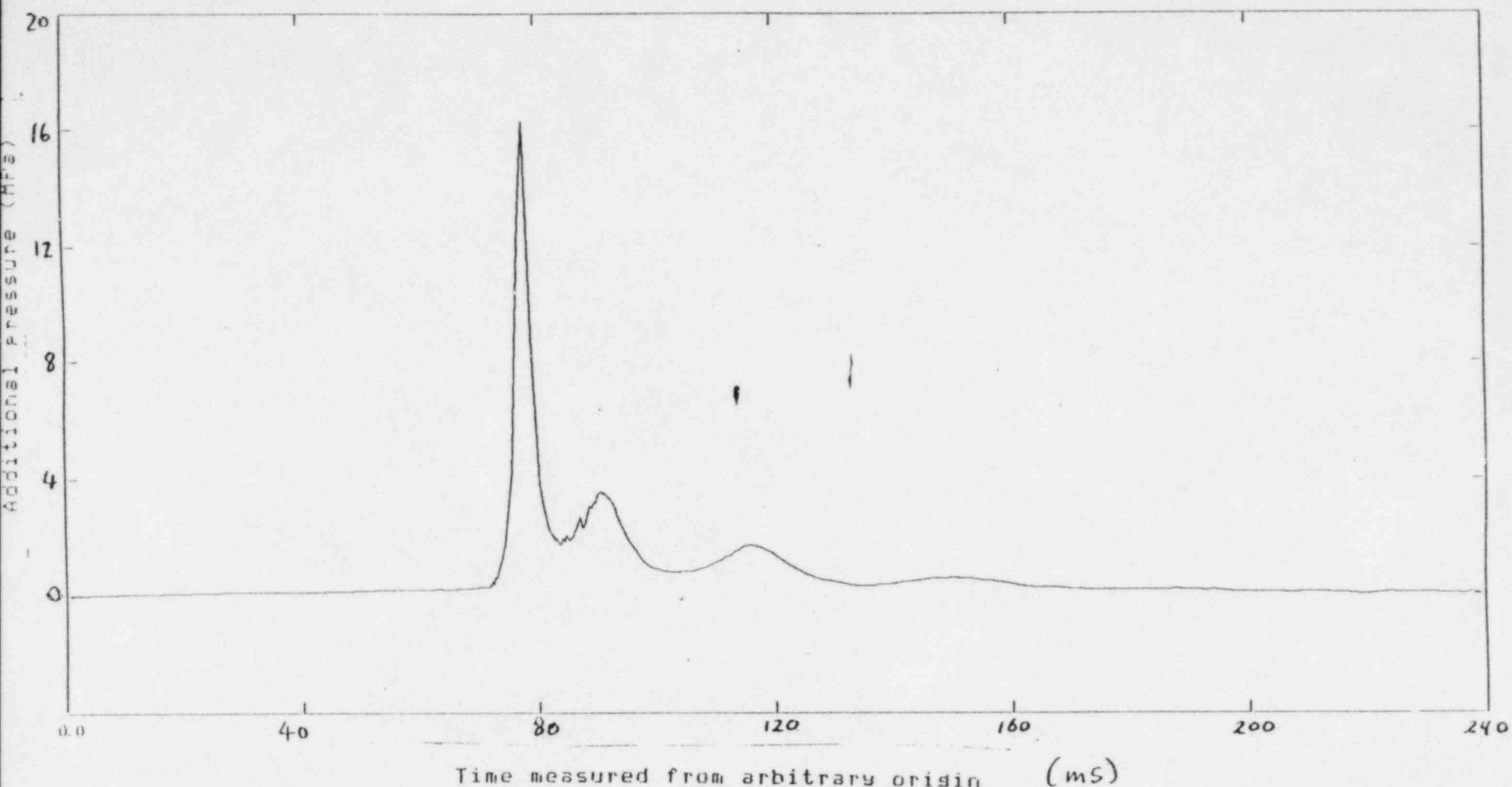

Figure 4. Cover gas pressure transient for triggered interaction observed in experiment SUW 09.

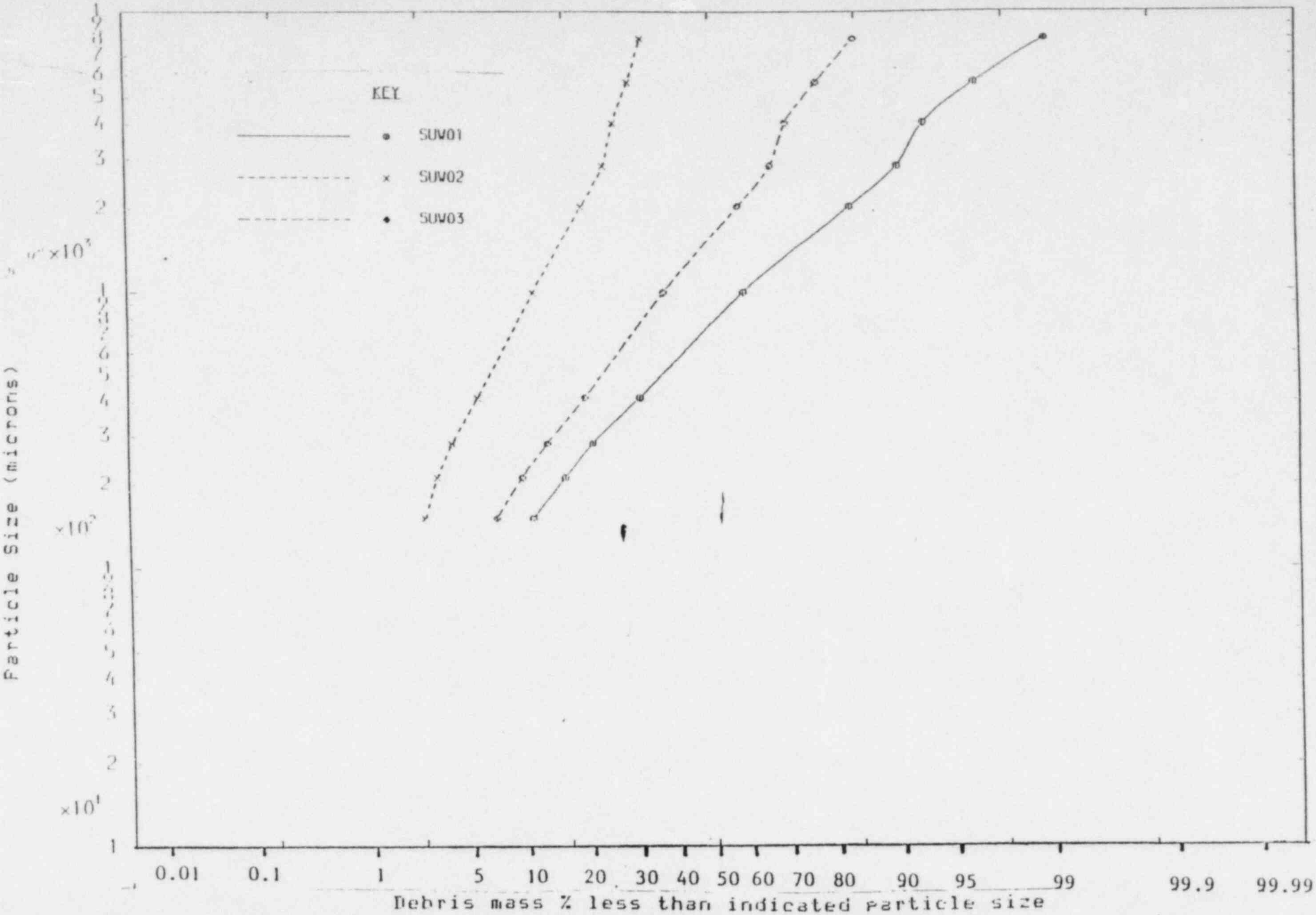

Figure 5. Cumulative particle size distributions for debris from free release experiments with 24 kg melts.

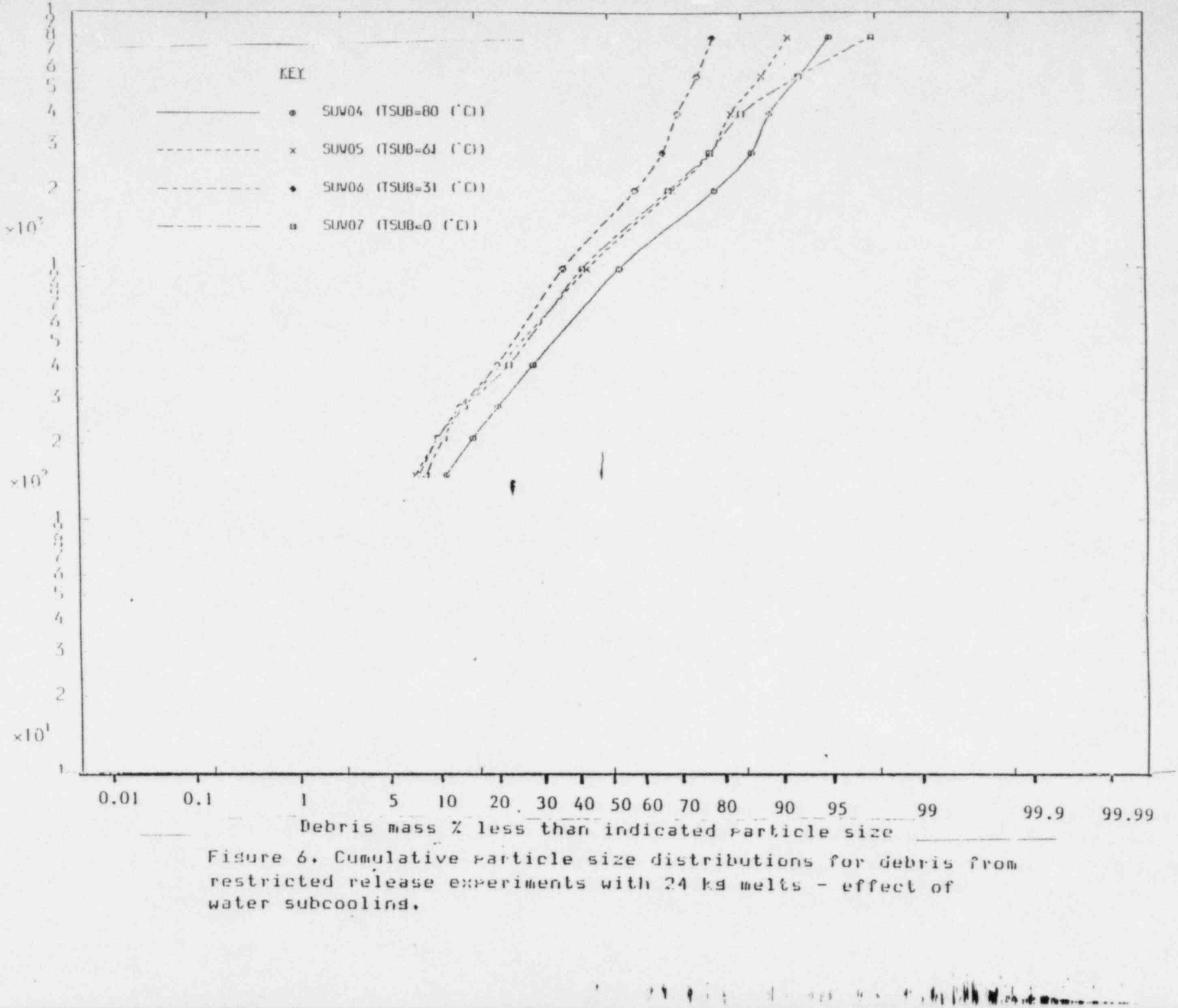

Figure 6. Cumulative particle size distributions for debris from restricted release experiments with 24 kg melts - effect of water subcooling.

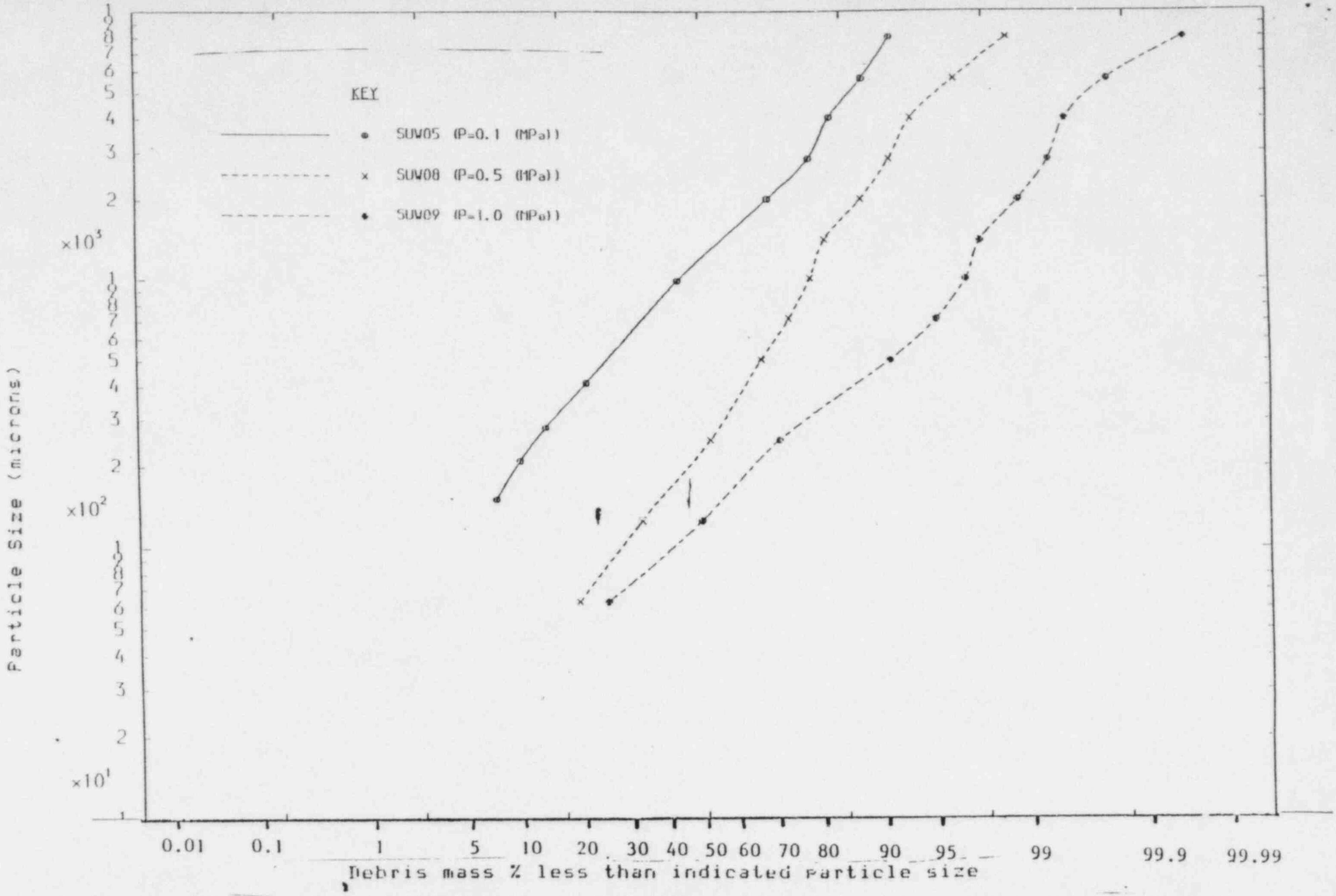

Figure 7. Cumulative particle size distributions for debris from restricted release experiments with 24 kg melts - effect of system pressure.

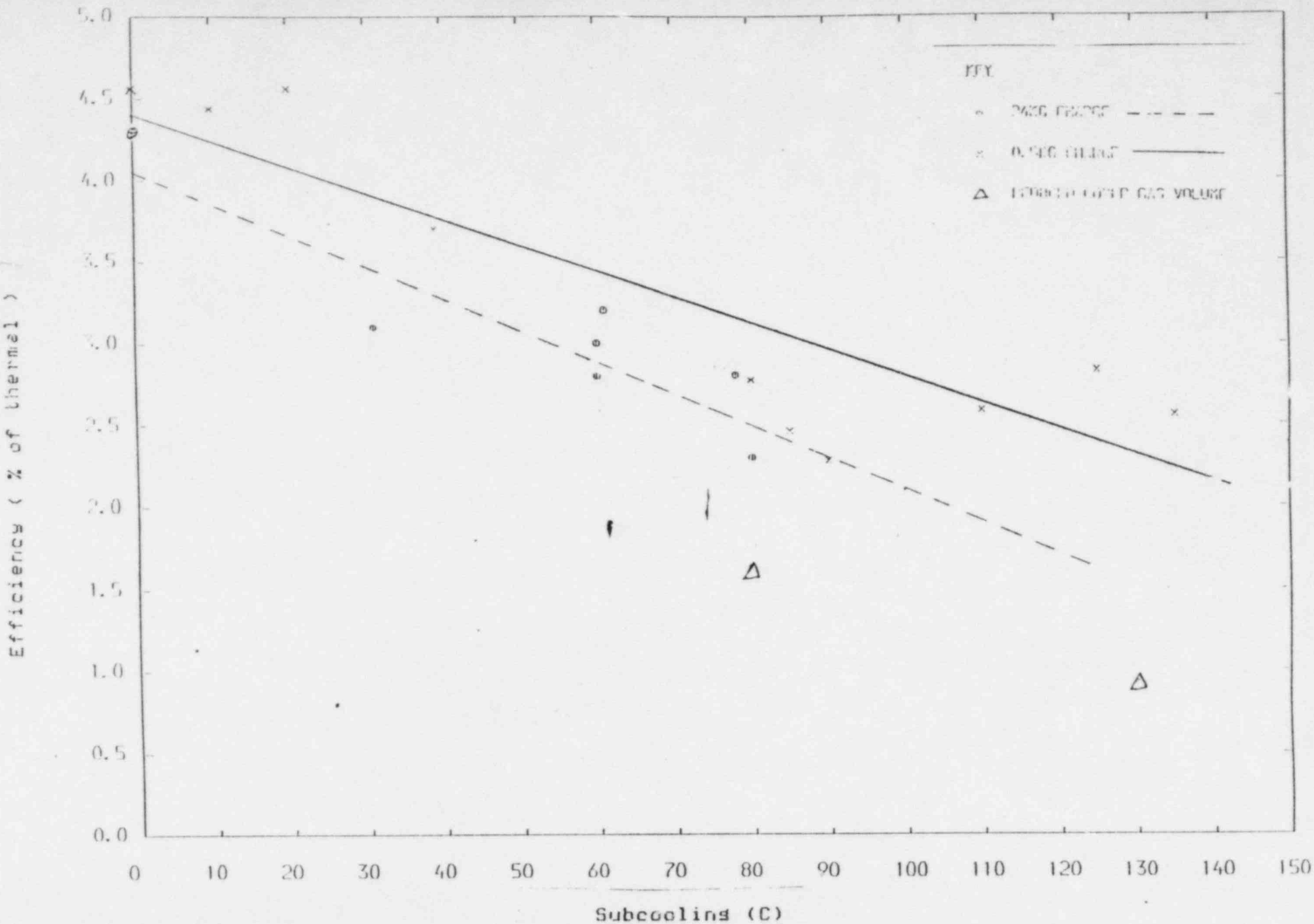

Figure 8. Interaction Efficiency as a function of water subcooling.

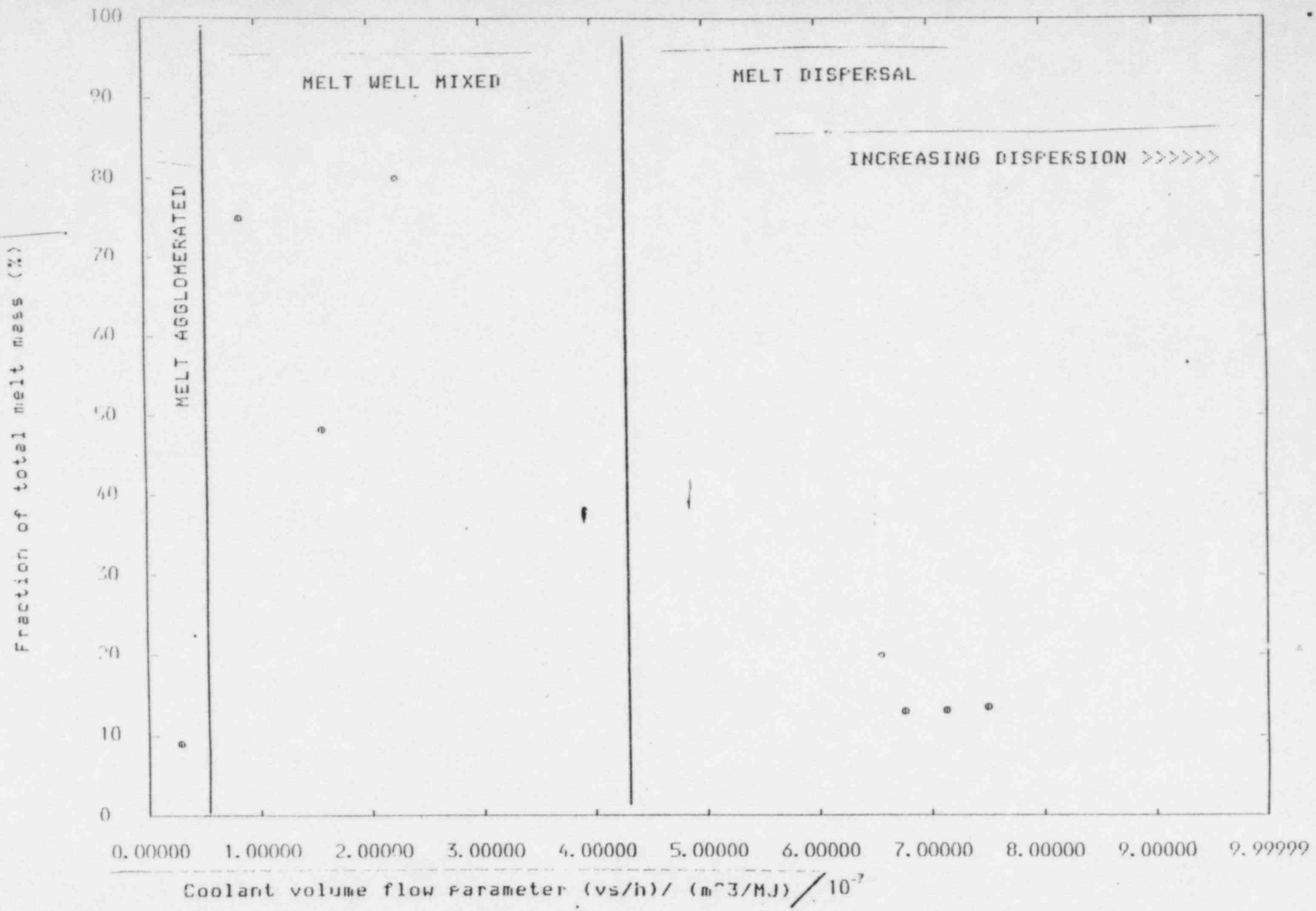

Figure 9. Fraction of total melt mass mixed, as a function of coolant vapour volume flow parameter vs/h, (or vs/3h for 8 kg melt).