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CHARACTERIZATION OF STEAM FOAM SURFACTANTS THROUGH ONE-DIMENSIONAL SANDPACK EXPERIMENTS

SUPRI TR 73

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May 1990

Performed Under Contract No. FG19-87BC14126

Stanford University
Stanford, California

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
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ABSTRACT

The efficiency of a steamflood may be increased by the use of surfactants that spontaneously generate steam foam when injected into an oil reservoir. Ideally the foam preferentally forms in high permeability streaks and oil depleted regions of the reservoir through which the steam would otherwise channel. The foam diverts the steam through regions previously uncontacted by the injected steam. This report describes an experimental programme conducted to study the foam-forming characteristics of a range of different surfactants. Both commericially-available, and experimental surfactants were tested in a one-dimensional sandpack under controlled conditions of pressures and temperatures similar to those encountered in California oil fields. Steam and nitrogen were continuously injected into the sandpack which contained neither clay nor oil. The surfactant solutions were injected in discrete slugs of a finite duration allowing transient phenomena such as the persistence of the foam to be studied.

Under the conditions of the experiment, long chain alpha olefin sulphonate surfactants were found to generate the strongest foams. Internal olefin sulphonates, linear toluene sulphonates and linear xylene sulphonate surfactants generated just as strong foams but only at successively higher concentrations. It was found that the strength of the foam produced by a surfactant of a particular chemical structure increased with increasing alkyl chain length.

The novel use of heat flux sensors attached to the outside of the sandpack allowed a better understanding of the heat transfer mechanisms operating within the system. Such an understanding is necessary if the experimental observations are to interpreted correctly.

1. INTRODUCTION

Poor sweep efficiencies are often encountered during steam floods. Like any other fluid, the injected steam will have a tendency to flow along the path of least resistance. As a result the steam will preferentially flow through any fractures and/or high permeability streaks which might be present in the oil reservoir. In those reservoirs that do not contain such features, the steam will have a tendency to form its own channel along the top of the reservoir. This phenomenon, known as *gravity override*, is caused by the difference in densities between the reservoir fluids and the injected steam. Once steam breakthrough occurs at one or more producing wells, progressively more and more of the injected steam will flow through these channels until the produced water to oil ratio is so high as to render the process uneconomic. Foam-forming surfactants enhance steam flood oil recovery by forming foam within these channels, and diverting the subsequently injected steam to other, previously-unswept regions of the reservoir.

Ideally the foam should spontaneously generate within the reservoir only in those regions that have been swept by the steam to some residual oil saturation. The foams should therefore be stable in the presence in relatively small amounts of oil, but should collapse at higher saturations. The foam should be stable over the range of temperatures and pressures encountered in the field. Surfactant retention by, and ion exchange with, the reservoir sands should be minimized where possible.

This report describes an experimental program during which the foam-forming ability of seventeen different surfactants were evaluated. The report begins by surveying the various laboratory techniques which have been used to evaluate the potential of steam foam surfactants. Several field applications of the steam foam process are then discussed. After outlining the project goals in Chapter 3, Chapter 4 describes the experimental apparatus and procedures employed during the course of the project. The experimental results are then discussed in Chapter 5. The foam-forming ability of each surfactant and the role of the non-condensible gas in stabilizing the foam is also addressed. The surfactants are then ranked according to their potential as foam-forming additives in Chapter 6. A discussion of the link between a surfactant's chemical structure and its ability to form foam is also presented. The report closes with concluding remarks that include recommendations for future work.

2. LITERATURE REVIEW

The results of many laboratory studies and field trials of a range of surfactant mixtures for the generation of steam foam within oil reservoirs have been reported in the literature over the last decade. This review chapter begins by examining a range of experimental techniques that have been used in the laboratory to assess the ability of a surfactant to generate and propagate steam foam within an oil reservoir. The results of some of the more important experimental investigations are then summarized. Special emphasis is placed on the establishment of a link between the chemical structure of a surfactant and its ability to form foam. The results of four steam foam field tests are then discussed. The four field tests are chosen because the surfactants used either are studied in this present work, or have similar chemical structures.

2.1. LABORATORY STUDIES

2.1.1. Experimental Techniques

In recent years a large number of laboratory investigations have been conducted to study the foam-forming ability of a range of surfactants under various conditions. The aims of these investigations have been to identify those surfactants that will spontaneously generate steam foam within porous oil reservoirs. A foam's strength and stability (characterized by its half-life) within an oil reservoir will depend upon such important factors as the steam flood temperature, surfactant and brine concentrations, nature and concentration of the oil, reservoir pressure, permeability and the reservoir cation exchange capacity. The foam strength and stability of an injected surfactant may be enhanced by the simultaneous injection of a non-condensible gas such as nitrogen, a sacrificial co-surfactant that will be retained by the reservoir matrix in preference over the foam-forming surfactant, and an electrolytic solution such as sodium chloride. Thus, to properly evaluate the foam-forming ability of a range of surfactants the laboratory experiments should be conducted under conditions as close as possible to those that will be encountered in the field.

In selecting the most appropriate surfactant for a particular application the main selection criteria should be:

- the surfactant and foam should be thermally stable under conditions likely to be encountered within the reservoir during the steam flood;
- the surfactant should not significantly partition into the oil; and,
- the retention of the surfactant within the porous medium should be low.

A carefully-planned sequence of surfactant screening tests will allow many candidate surfactants to be eliminated early during an experimental program. Castanier and Brigham (1985) and Doscher and Hammershaimb (1985) describe examples of useful screening tests. After a series of screening tests McPhee *et al* (1988) were able to eliminate all but eight surfactants from an initial total of 109, during a study to select surfactants for use in generating foam under North Sea conditions.

The next stage in evaluating the potential of a particular surfactant involves the use of a one-dimensional sandpack model. The model typically consists of a cylindrical sandpack, initially saturated with water only, through which steam is injected against a known back pressure. Steam foam is either injected pre-formed, or is allowed to spontaneously form within the sandpack. Steam of a known quality, surfactant of a known concentration, and non-condensible gas and an electrolytic solution, if any, are then injected continuously into the sandpack. The pressure and temperature conditions within the sandpack are continuously monitored. Any increase in the pressure gradients within the sandpack indicates the generation of foam within the porous medium. As surfactant injection continues the pressure gradients increase within the system until a steady state condition is attained. The steady state pressure profile within the sandpack then forms the basis for assessing the foam-forming ability of the surfactant. Such experiments are usually performed in the first instance in the absence of oil. This is because it is easier to perform the experiments in the absence of oil, and should a surfactant fail to foam in the absence of oil then it is most unlikely that it would foam in its presence. Thus more surfactants may be eliminated from further consideration at this stage.

While the results of such steady state experiments are useful in ranking surfactants according to the maximum pressure drops or gradients that they induce within a sandpack, they can not be used to observe transient foam behavior such as foam persistence and foam decay rates. In a slightly modified version of the above experiment, the surfactant is not injected into the sandpack continuously, but in slugs of a discrete size. (A slug size of ten percent of the sandpack pore volume is typical). The sandpack is first steam-flooded. A non-condensible gas is then injected continuously with the steam. A slug of the surfactant solution of a known concentration is then injected and the pressure and temperature profiles within the system are monitored. After a known volume of the surfactant solution has been injected, surfactant injection is stopped while the injection of steam and the non-condensible gas continues. In some cases the foam generated within the system during the injection of the surfactant slug collapses immediately after surfactant injection is stopped. In other cases however, the generation of foam within the sandpack continues, with the pressure gradients within the sandpack increasing for some considerable time after surfactant injection has ceased.

Foam enhances a steam flood by diverting the injected steam away from areas of low oil saturation. Since foam stability decreases with increasing oil saturation the foam will be strongest in regions of low oil saturation. Simple one-dimensional sandpack models can not be used to study the extent of such diverting phenomena. Rather than use two-dimensional sandpack systems, a number of workers have used two one-dimensional sandpacks connected in parallel (Dilgren and Owens, 1986). In a typical application of the technique two sandpacks or cores of very similar porosities and permeabilities, are connected in parallel to a common source of steam, surfactant and non-condensible gas. The two sandpacks are then saturated to different extents with oil. The relative production rates of oil in the presence and absence of the surfactant then indicate the effectiveness of the foam as a steam diverter. As an example of this technique, Huang *et al* (1985) prepared two parallel sandpacks with oil saturations of 35 and 20 percent. In a test without the use of a foaming agent 71.7 percent of the injected steam flowed through the low saturation cell, however, when a surfactant was introduced into the two sandpacks, only 15.4 percent of the injected steam passed through that sandpack.

While parallel one-dimensional sandpacks are useful in isolating the effect of oil saturation on the foam-forming process, they can not be used to study processes involving gravity override. The phenomenon of gravity override must be studied using two-dimensional vertical sandpacks. A two-dimensional vertical sandpack is typically prepared by packing a rectangular container with carefully sized sand. If gravity override is to be studied then the sandpack will be homogeneously filled with sand so that the porosity and permeability within the sandpack is uniform. High permeability streaks may be simulated within two-dimensional sandpacks by preparing the pack with carefully graded sand. An excellent description of the preparation of a two-dimensional sandpack is given by Mahmood and Brigham (1987). Zirritt *et al* (1985) used such a two-dimensional sandpack to show that the generation of foam within the porous medium significantly reduced gravity override and viscous fingering and increased oil recovery from the sandpack.

For adequate diversion of steam within a reservoir, it is important to ensure that the foam can pass out into the reservoir away from the injection well. In reservoirs in which the formation sands possess a high cation exchange capacity and a high divalent-cation content, cation exchange between the injected surfactant solution and the formation clays can significantly limit the extent to which the surfactant can reach into the reservoir. As Lau and O'Brien (1988) observed, this is because the monovalent cation in the surfactant solution can exchange with the divalent cations on the clays, resulting in an increase in the concentration of the divalent cations, such as Ca^{++}, in the aqueous phase. This buildup in the divalent cation concentration can lead to partitioning and/or precipitation of the surfactant, thus reducing the amount of surfactant available to form foam within the reservoir. It is therefore very important before using a surfactant in the field to test the extent to which it will be retained by the clays in the formation sands. This is typically done by using a one-dimensional sandpack prepared from reservoir sands, rather than pure quartz. As the retention of the sands and not the strength or stability of the foam, is being tested, the tests may be performed without the injection of steam. The surfactant is injected into the hot sandpack and the effluent fluids are analyzed for their surfactant and cation content. Lau and O'Brien, and Lau and Borchardt (1989) found that the combined effects of surfactant partitioning, precipitation and adsorption can lead to substantial retardation of the surfactant, and hence the foam, propagation rate. They further found that partitioning of two particular surfactants increases with increasing Ca^{++} concentration, but decreases with increasing the concentration of NaCl injected with the surfactant.

A thorough experimental program to evaluate the foam-forming ability of a surfactant for use in a particular reservoir will involve the use of the above experimental procedures. However, because the foam-forming ability of a surfactant is so sensitive to such factors as the nature and concentration of the oil, and the clay content of the porous medium, meaningful comparisons between the observations of different workers can only be made when the experiments are conducted using clean, quartz sand in the absence of oil.

2.1.2. Experimental Results

A number of workers have reviewed the results of the many experimental studies that have been undertaken to study the foam-forming ability of surfactants. Marsden *et al* (1977) reviewed relevant papers and patents published before 1977. This review was later updated by Marsden (1986) and then Wang and Brigham (1986). It is worth discussing here however some of the more significant papers.

A sandpack prepared from clean quartz sand was used by Dilgren *et al* (1978) to study the foam-forming ability of a small number of surfactants. The sandpack used was 1 inch long and 12 inches in diameter. Of those tested **Siponate DS-10**, sodium dodecylbenzene sulphonate, and **TRS-12B**, a petroleum sulphonate, generated the strongest foams. It is interesting to note that even though **DS-10** generated the stronger foam, the residual oil saturation following the **DS-10** experiments was three to four times higher than following the use of **TRS-12B** which produced a slightly weaker foam. The workers also noted that the presence of the reservoir oil within the sandpack had a significant, but relatively modest, tendency to limit the extent of the permeability reduction caused by the foam. Also, it was observed that at least for these surfactants, the presence of an electrolyte enhanced the reduction in permeability to the steam. Finally, they noted that the injection of even small amounts of a non-condensible gas strengthened the foams.

Later Dilgren and Owens (1983) found that alpha olefin sulphonate surfactants produced stronger foams than **Siponate DS-10** tested earlier. They recommended that the surfactant molecules contain alkyl chains with between 10 and 24 carbon atoms. Using a sandpack 1¼ inches in diameter and 11 inches long, they found that in the absence of oil, the addition of an alpha-olefin sulphonate reduced the steam mobility by a factor of 25.

Further work using one-dimensional sandpacks conducted by Muijs and Keijzer (1987) indicated that linear C_{25} - C_{30} alpha olefin sulphonate surfactant produce stronger foams than their shorter C_{16} - C_{24} counterparts. A sandpack 15¾ inches in diameter and 11 inches long and having a permeability of 8 D was used in the laboratory program. When ninety percent quality steam was injected at a rate of 600 ml/min against a back pressure of 290 psig a pressure gradient of 4.0 psi/ft was generated. Injection of a 0.5 wt % solution of a linear C_{20} alpha olefin sulphonate surfactant with the 90 % quality steam generated an average pressure gradient of 103 psi/ft within the sandpack, with a maximum gradient of 242 psi/ft being generated near the outlet. When a 0.5 wt % solution of a longer, linear C_{26} alpha olefin sulphonate surfactant was injected with the steam in place of the C_{20} surfactant, the average pressure gradient across the sandpack increased to 180 psi/ft, with a maximum pressure gradient of 296 psi/ft being observed near the outlet.

The results of an experimental program conducted by Duerksen *et al* (1985) suggest that superior foam is formed by the injection of alpha olefin sulphonate dimers. The dimers are formed from monomers having a carbon chain length of between 5 and 24, with the most preferred monomers being $C_{15} - C_{20}$ alpha olefin sulphonates. The workers used a ¼ inch diameter, 2½ inch long stainless steel pack containing brine and Kern River crude oil at 204°C (400°F) to evaluate the foam-forming performance of a range of surfactants. They found that a dimer of $C_{11} - C_{14}$ alpha olefin sulphonate produced stronger foam than that produced by a linear $C_{15} - C_{20}$ alpha olefin sulphonate. Also dimers of longer alpha olefin sulphonates were observed to produce even stronger foams. In the same experimental program, foam strength was observed to increase with molecular weight for the three alkyl toluene sulphonates tested. Further tests conducted using a ¾ inch diameter, 6 inch long sandpack saturated with heavy Kern River crude oil and water confirmed the superiority of the dimer surfactants. Using **Stepanflo 30**, a $C_{16} - C_{18}$ linear alpha olefin sulphonate as a base case, the use of a dimer of $C_{11} - C_{14}$ alpha olefin sulphonate surfactant generated foam 2.4 times as strong, while a dimer of $C_{15} - C_{18}$ alpha olefin sulphonate generated foam 2.8 times stronger than the base case.

After an laboratory program of thirty-one sandpack experiments Huang *et al* (1985) recommended the use of surfactants of the following structure to generate steam foam within an oil reservoir:

$$RO\,(R^1O)_n\,R^2\,SO_3^-\,M^+$$

where R is an alkyl radical, either branched or linear, or an alkylbenzene, alkyltoluene or alkylxylene group having between 8 and 24 carbon atoms in the alkyl chain, R^1 is ethyl, propyl, or a mixture of ethyl and propyl, n is between 2 to 5, R^2 is ethyl, propyl, hydroxypropyl or butyl, and M is an alkali metal or the ammonium cation. The workers found that surfactants of their invention produced far stronger foam and recovered more oil from the sandpack than the surfactants **Thermophoam BWD, Siponate 301-10** and **Stepanflo 20.** These tests were performed in a sandpack 35.4 inches (90 cm) long and 1 inches (3.4 cm) in diameter and having a porosity of 40 % and an initial oil saturation of 20 %. Steam was injected at 4 ml/min cwe while nitrogen was injected at a rate of 16.8 ml/min. In a further series of tests the workers studied the importance of injecting a non-condensible gas such as nitrogen to stabilize the foam. They found in nearly all cases that increasing the injection rate of the nitrogen into the sandpack significantly increased the pressure drop across the pack.

Muijs *et al* (1988) conducted a series of sandpack experiments to study the foaming properties of a range of surfactants with a view to establishing a link between the ability of a surfactant to foam foam and its chemical structure. The experiments were conducted in the absence of oil within sandpacks 4 inches (10 cm) to 15¾ inches (40 cm) in length. During most of the experiments steam was injected against a back pressure of 290 psig corresponding to a steam saturation temperature of 215°C (419°F). Some of the more important findings of the work are as follows:

- Against a back pressure of 290 psig and with 90 % quality steam being injected at 600 ml/min without an electrolyte, a $C_{24} - C_{26}$ alpha olefin sulphonate was observed to foam more strongly than its shorter counterparts. A pressure drop of 255 psig was generated across the sandpack in response to the continued injection of a 0.5 wt % solution of the $C_{24} - C_{26}$ preparation, compared to a pressure drop of only 136 psig for a C_{20} alpha olefin sulphonate. No increase in the pressure drop across the pack was observed when a $C_{16} - C_{18}$ preparation was injected.
- The pressure drop generated across the sandpack was observed to increase with increasing alkyl chain length when four different linear toluene sulphonate preparations were injected with 80 % quality steam and 0.5 % NaCl. The injection of a 0.5 wt % solution of a C_{16} linear toluene sulphonate did not yield an increase in the pressure drop across the sandpack while the injection of C_{18}, $C_{20} - C_{24}$, and $C_{24} - C_{28}$ preparations resulted in pressure drops of 145 psi, 239 psi and 304 psi being observed across the sandpack.
- The injection of **Chevron's Chaser SD1000**, a dimerised alpha olefin sulphonate of the type recommended by Duerksen *et al* (1985), produced foam stronger than the C_{18} linear toluene sulphonate, but considerably weaker than the $C_{20} - C_{24}$ linear toluene sulphonate.
- Several experiments were performed at temperatures between 150°C (302°F) and 290°C (554°F) to study the effect of temperature on the strength of the foam formed by linear toluene sulphonate surfactants. For three surfactants of different molecular weights, the pressure drop generated within the pack was found to be sensitive to temperature, passing through a maximum value at some temperature. The temperature at which the maximum pressure drop was generated increased with increasing molecular weight, as did the magnitude of the maximum pressure drop. For the C_{18} linear toluene preparation, the maximum observed pressure drop was 171 psi, recorded at 190°C (374°F). The maximum pressure drop for the $C_{20} - C_{24}$ preparation was also observed at 190°C and was 259 psi. For the heaviest of the three surfactant preparations tested, the $C_{24} - C_{28}$, the maximum pressure drop recorded was 354 psi at 220°C (428°F). Above these temperatures the strengths of the foams formed decreased significantly: at 270°C (518°F) the C_{18}, $C_{20} - C_{24}$ and $C_{24} - C_{28}$ preparations produced pressure drops of only 6, 13 and 117 psi respectively. Also, below about 160°C (320°F) the $C_{20} - C_{24}$ formulation produces stronger foam than the $C_{24} - C_{28}$ formulation.

The above experiments of Muijs *et al* were performed in the absence of oil. Also, the reported pressure drops were the maximum steady state values observed in response to the continuous injection of the surfactant solutions. Transient phenomena such as foam persistence and foam decay rates are not reported by the workers.

The rate at which surfactants, and hence foam, propagates through a reservoir will be significantly reduced if the clays contained within the reservoir have a significant ion exchange capacity. The transport of surfactant through the reservoir may be impeded if the surfactant's monovalent ions are exchanged with the divalent ions of the clays. The surfactant's progress through the reservoir is limited by precipitation, partitioning and by retention due to ion exchange. To overcome these problems Dilgren and Owens (1987) suggested injecting with the foam-forming surfactant, a sacrificial co-surfactant such as a alkylpolyalkoxyalkylene. The workers reported the results of a series of experiments during which different surfactants were injected through a sandpack containing 2000 ppm Ca^{++}. Even after injection of ten pore volumes of a 0.5 wt % solution of **Siponate A-168**, a branched alpha olefin sulphonate, no foaming was observed and only five percent of the surfactant was produced, suggesting that 95 % was made unavailable by ion exchange. The experiment was then repeated but with one-fifth of the surfactant replaced with an alkylpolyalkoxyalkylene sulphonate, NES-25. After injection of the new surfactant formulation foaming occurred within the sandpack with the permeability reduction factor being 0.051 ± 0.011.

Lau and Borchardt (1989) reported on an experimental investigation conducted to develop a surfactant formulation better at generating steam foam within Kern River oil fields 'than **Shell's Enordet AOS 1618**, an alpha olefin sulphonate surfactant containing between 16 and 18 carbon atoms on the alkyl chain. The authors sought to improve the oil recovery process by increasing the rate of surfactant propagation through the reservoir, increasing the foam strength, and decreasing the residual oil saturation left after the steam foam process. To achieve this they used three experimental techniques that involved flooding sandpacks of Kern River formation sand. Two co-surfactants, **NES-25** and **NES-30** were studied for increasing surfactant propagation by acting as sacrificial surfactants. These surfactants are linear alkylethoxyethyl sulphonates with 2.5 and 3.0 ethoxy units per molecule respectively. They found that including a small amount of the co-surfactants in the surfactant preparation improved surfactant propagation, but not sufficiently to warrant the extra costs involved. An alkaline steam foam formulation was studied that consisted of AOS 1618 and trona ($Na_2CO_3.NaHCO_3.2H_2O$). The workers found that the addition of the trona caused the divalent cations that were ion exchanged off the formation clays to be precipitated as calcium and magnesium carbonates. Partitioning and precipitation of the surfactant was therefore reduced. A series of experiments were also performed using **AOS 2024** instead of AOS 1618. The foam generated by the heavier surfactant was stronger and resulted in a lower residual oil saturation than its lighter counterpart, but the surfactant propagation rate was slower. To overcome this the authors suggested injecting Na_2SO_4, and not NaCl, with the surfactant. Since $CaSO_4$ is only slightly soluble in water at elevated temperatures injecting sulphate ions would precipitate most of the calcium ions that are ion exchanged off the clays before those ions could attack the injected surfactant.

Lau (1988) recommended that high cation exchange capacity reservoirs be flushed with an alkali such as trona before injection of the foam surfactant. Where this is not possible the alkali should be injected with the surfactant. Lau lists the three major benefits of alkali-enhanced steam foam as:

- the surfactant propagation rate is increased because the trona ion exchanges with, then precipitates, the multivalent cations of the clays that would have otherwise attacked the surfactant.
- surfactant retention due to adsorption on the rock surface is reduced. The high pH generated by the alkali causes the clay surfaces to be more negatively charged, thus reducing adsorption of the anionic steam foam surfactant.
- the residual oil saturation is lowered due to emulsification of oil into small drops caused by the action of steam, alkali and a surfactant. Micromodel flow studies suggest that the size of these oil drops can be smaller than the size of a pore throat, thus making their dispacement much easier.

Lau favors the use of trona over other alkali solutions because:

- the consumption of alkali by clay transformation is reduced. (Clay components such as kaolite and montmorillonite can react with alkali to form zeolites.)
- when in contact with steam, trona generates the non-condensible CO_2 which helps to maintain a stronger foam.
- the generation of CO_2 either reduces or entirely eliminates the need for the additional injection of a non-condensible gas such as nitrogen.

To illustrate the advantage of using trona two almost identical sandpack experiments were performed using packs prepared from clean Ottawa sand that had been steam flooded to obtain a residual oil saturation. In one experiment, 50 % quality steam, 0.6 mol % nitrogen in the vapor phase, 6 wt % Na_2CO_3 and 0.25 wt % Enordet AOS 1618 were injected into the sandpack. In the second experiment no nitrogen was injected, and 10 wt % trona was injected in place of the Na_2CO_3. The results showed that even in the absence of nitrogen, the addition of trona produced a foam with a higher apparent viscosity than that produced by the injection of the nitrogen and the Na_2CO_3 with the surfactant.

2.2. FIELD TRIALS

A wide variety of surfactants have been employed within oil reservoirs to generate steam foam. Not all applications have met with success. Recently Eson and Cooke (1989) and Castanier (1989) have surveyed the use of foams to increase oil recovery from a steam flood. Some of the more important field projects are reviewed here.

A steam foam field test using **Suntech IV**, a synthetic alkyl toluene sulphonate, was reported by Yannimaras and Kobbe (1988). The test was performed in two 5-spot patterns in the Winkleman Dome Nugget Field, Wyoming. The oil and reservoir characterists are summarized in Table 2.1. The field had previously been subjected to a steam flood and the two patterns chosen for the test had exhibited severe channeling. In both tests, methane was injected as a non-condensible gas to help stabilize the foam. A 15 wt % solution of the surfactant was injected into the first pattern and a significant increase in oil recovery was observed. Steam channeling was controlled and all wells responded to the treatment. The large increase in oil production rates from the pattern may in part have been due to the re-opening of one of the production wells that had been shut-in for some time. A 35 wt % solution was injected into the second pattern. The more concentrated solution was used purely to reduce shipping costs. Seven months after injection of the surfactant solution had begun there was no discernible increase in the oil recovery. Initially, the operators had problems separating an oil-in-water emulsion created by the surfactant and the reservoir oil, but the problem was solved by the use of Tretolite.

The results of two successful steam foam field tests conducted by Chevron in the Midway-Sunset Field of California are reported by Ploeg and Duerksen (1985). In both tests Chevron's dimerised alpha olefin sulphonate, **Chaser SD1000** was used. The field and oil properties of the two test areas are summarized in Table 2.2. During both tests 50 to 60 % quality steam was injected continuous into the patterns while nitrogen and the surfactant were injected in slugs lasting for two days, once a week. Following injection of 15 slugs into Section 15A and 20 slugs into Section 26C, oil production from the patterns increased significantly. At the conclusion of the work the operators concluded that the injection of the non-condensible nitrogen was useful in stabilizing the foam. Surfactant concentration as low as 0.1 wt % generated effective foams while the sulphonate did not cause any oil handling or treating problems. Finally they concluded that the oil produced as a result of the steam-diverting foam was bypassed oil that would not have been economically produced otherwise.

Table 2.1 : Oil and Reservoir Properties of Winkleman Dome Nugget Field, Wyoming after Yannimaras and Kobbe (1988)

Depth	1225 ft	(373 m)
Net pay thickness	80 ft	(24 m)
Average formation thickness	180 ft	(55 m)
Average porosity	22.8%	
Permeability	481 md	
Original reservoir temperature	27°C	(81°F)
Oil gravity	14°API	
Oil viscosity at 27°C	800-1000 cP	

Table 2.2 : Oil and Reservoir Properties of Potter Sand, Midway-Sunset Field, California after Ploeg and Duerksen (1985)

Location	Section 15A		Section 26C	
Depth	1110 ft	(335 m)	1200 ft	(366 m)
Average net pay thickness	310 ft	(94 m)	260 ft	(79 m)
Average gross thickness	200-500 ft	(61-152 m)	600 ft	(183 m)
Average porosity	36.5%		29%	
Permeability	3900 md		1390 md	
Reservoir pressure	75 psig	(618 kPa)	75 psig	(618 kPa)
Oil gravity	13°API		14°API	

Based upon a series of laboratory experiments, Shell's **Enordet AOS 1618**, an alpha olefin sulphonate was chosen for a steam foam pilot test within the massive Potter Sands of California's Midway-Sunset Field. Mohammadi *et al* (1987) report that the pilot area consisted of four inverted five-spot patterns in a field that had earlier been steam flooded. The reservoir characteristics are presented in Table 2.3. Surfactant, brine and nitrogen were simultaneously injected with sixty percent quality steam into each of the four patterns. The continuous injection of the foam-forming mixture resulted in a significant increase in oil production from the pilot producers and from three of the first line peripheral wells.

Enordet AOS 1618 was also used to generate steam foam within the Mecca and Bishop leases in the Kern River Field. Patzek and Koinis (1988) reported that steam foam was generated in both pilots by the continuous injection of 50 % quality steam containing 4 wt % NaCl and 0.5wt % of the surfactant. 0.06 mol % of nitrogen was simultaneously injected. The brine was injected to help counter the reservoir's high ion exchange capacity. The oil and reservoir properties of both pilot areas are summarized in Table 2.4. Because of an aggressive steam flood started on adjacent leases by other operators difficulty was encountered in analyzing the production data to assess the amount of addition oil produced by the steam foam test in the Mecca Sand. The authors concluded that the steam foam project resulted to the additional recovery of 8.5 % of the original oil in place. The authors also estimate that an additional 14 % of the original oil in place was produced from the Bishop Q Sand by the pilot project, but a significant proportion of this incremental oil must have been as a result of the drilling of additional production wells. Patzek and Koinis concluded that there were major oil responses observed in both pilot areas due to the injection of the surfactants. Well logs indicated that the vertical sweep efficiency of the steam was significantly improved, but the residual oil saturation to the foam was similar to that to steam, being about ten percent. The workers also concluded that the growth of the foam within the pilot areas was limited by the availability of the surfactant which was in turn, retained on the high ion exchange capacity reservoir sands.

2.3. CONCLUDING REMARKS

From the survey of experimental techniques it has been shown that one-dimensional sandpack models give good indications of the foam-forming ability of surfactants. The increased complexities that accompanies the use of two-dimensional models are only justified once a surfactant has been identified by one-dimensional tests as being a good steam foamer. A number of workers have shown that the potential of a surfactant to form a strong foam may be severely limited by interactions between the surfactant and the reservoir clays. The ability of a surfactant to generate and propagate foam through a reservoir depends upon the extent and nature of both the reservoir clay and the oil. While it is important to test surfactants in the presence of reservoir oil and clay, it would not be possible to meaningfully compare the results of various workers, unless all experiments were conducted using the same concentrations of similar oils and clays. For this reason it is often more appropriate to conduct foaming experiments in the absence of both oils and clays. Only later, when a particular reservoir is being targeted for recovery by steam foam should oil and clay be included. Finally, the survey of experimental techniques shows that in nearly all one-dimensional sandpack experiments conducted to study the foam-forming ability of a range of surfactants, the surfactants are injected continuously, until a steady state pressure profile is obtained. Such steady state methods do not allow transient phenomena such as foam persistence and foam decay to be studied.

From the survey of experimental results it has been shown that surfactants of many different chemical structures have been tested. In some cases the use of additional sacrificial co-surfactants has been considered. Based upon the work of a number of independent investigators there is an apparent link between a surfactant's chemical structure and it's ability to form a strong foam. Various workers have shown that the foam strength increases with

Table 2.3 : Oil and Reservoir Properties of the Pilot Area in the Potter Sand of the Midway Field, California, after Mohammadi *et al* (1987)

Depth	1600 ft	(488 m)
Net pay thickness	437 ft	(133 m)
Average porosity	34%	
Oil gravity	11.2°API	
Reservoir Dip	14-18°	

Table 2.4 : Oil and Reservoir Properties of the Mecca and Bishop Pilot Areas after Patzek and Koinis (1988)

	Mecca M sand		Bishop Q Sand	
Depth	1000 ft	(305 m)	600 ft	(183 m)
Average net pay thickness	74 ft	(23 m)	65 ft	(20 m)
Average gross thickness	83 ft	(25 m)	99 ft	(30 m)
Average porosity	30%		30%	
Cation exchange capacity	4 meq/100g		9 meq/100g	
Oil gravity	13°API		13°API	

increasing alkyl chain length: this was clearly shown to be true for alpha olefin sulphonates by Muijs and Keijzer (1987), and Muijs *et al* (1988). Muijs *et al* also showed that the foam forming ability of a surfactant is temperature-dependent.

Finally, the survey of field trials of steam foam-forming additives shows that a range of surfactants have been successfully used to generate steam foam within oil reservoirs. In addition the foam so generated, has led to increased oil recovery by diverting the injected steam to regions of the reservoir that would not have otherwise been swept. In Chapter 5 the foam-forming ability of a range of fifteen surfactants will be compared to those of Chevron's **Chaser SD1000** and Shell's **Enordet AOS 1618**, two surfactants whose use in the field has been reported.

3. PROJECT DEFINITION AND AIMS

A number of successfully steam foam field projects have proved the economic viability of injecting foaming surfactants to enhance oil recovery. The injected foam generates preferentially in regions of low oil saturations, resulting in the diversion of the injected steam into previously unswept regions. The incremental oil produced is from regions of the reservoirs that would not otherwise have been economically produced.

Many surfactants have been developed for use in spontaneously generating foam within oil reservoirs. Chemical manufacturers make competing claims about the performance of their surfactant products. There is clearly a need for an independent study to compare the foam-forming ability of a range of surfactants. Because the ability of a surfactant to form foam is very sensitive to the nature and concentration of any oil and clay present, the applicability of experimental observations made in their presence will be extremely limited. As a consequence, the experimental research program undertaken in the present study is conducted in the absence of oil using clean quartz sand. In order to study transient foam behaviour such as foam persistence and foam decay, the surfactants are not injected continuously, but are injected in discrete slugs.

The experimental program reported in this report has the following aims:

- to study the foam-forming ability of a range of surfactants under a set of standard conditions
- to study the effect of non-condensible gas on foam stability
- to rank the tested surfactants according to the strength of the foam they generate within the sandpack
- to establish a link between the foam-forming ability of a surfactant and its chemical structure
- to study heat transfer mechanisms operating within the sandpack model. Such an understanding is important to correctly interpret experimental observations.

4. EXPERIMENTAL APPARATUS AND PROCEDURE

The foam-forming characteristics of a range of surfactants may be studied using a one-dimensional sandpack model. Discrete surfactant slugs of a finite duration are injected into the sandpack whilst steam and nitrogen are continuous and simultaneously injected. Any increase in the pressure drop across the length of the sandpack indicate the generation of steam foam within the pack. This section describes the experimental apparatus used, and the procedures followed, during the investigation. A summary of the experimental program is also presented.

4.1. APPARATUS

The one-dimensional sandpack model, presented in Fig. 4.1, essentially consists of the sandpack, the injection system, the production system, and a data acquisition system. These four sections are now discussed. The apparatus is essentially the same as that used by Wang and Brigham (1986) and Maneffa (1987).

4.1.1. Sandpack

The one-dimensional sandpack is formed by filling a horizontal stainless steel tube with clean sand. The tube has an average inside diameter of 2.16 inches (54.8 mm), an outside diameter of 2.25 inches (57.2 mm), and a length of 72 inches (1.830 m). The sandpack used has a porosity of 33.0 percent and an absolute permeability of 91.0D. The total pore volume within the tube is 1420 ml. The sand size distribution is presented in Table 4.1. The same sandpack was used for all experiments. It was cleaned between experiments using a procedure outlined in Section 4.2.4.

The sand is retained by wire screens located at each end of the tube. The tube is sealed at both ends using brass O-rings and was successfully pressure tested to 350 psig (2.5 MPa). Once sealed the tube is not opened until the entire program of experiments is complete. To minimize heat losses to the surroundings the entire length of the tube is uniformly wrapped with approximately 2¾ inches (7 cm) of a fibrous insulation material.

4.1.2. Injection System

Distilled water is supplied to the steam generator at a constant rate by a Constametric pump. The generator consists of a helical tube wound inside an annular furnace. The furnace is operated so that under normal operating pressures slightly superheated steam is generated. The tubing between the steam generator and the sandpack is insulated to minimize heat losses from the line.

A second Constametric pump is used to inject the surfactant solution at a controlled rate into the sandpack. A 14 µm filter in the pump inlet line protects the pump from foreign matter. The pump is fed with the surfactant solution from a nearby flask. The flask may be set upon a heater/stirrer to ensure that the surfactant remains in solution during injection. The surfactant injection line is also valved so that the surfactant injection pump and line may be primed with the surfactant solution prior to injection.

Table 4.1 : Sand Size Distribution

U.S. Mesh Number	Hole Size (mm)	Mass Fraction Retained
20	833	0.002
35	495	0.480
40	417	0.286
60	246	0.220
80	180	0.006
pan	--	0.002

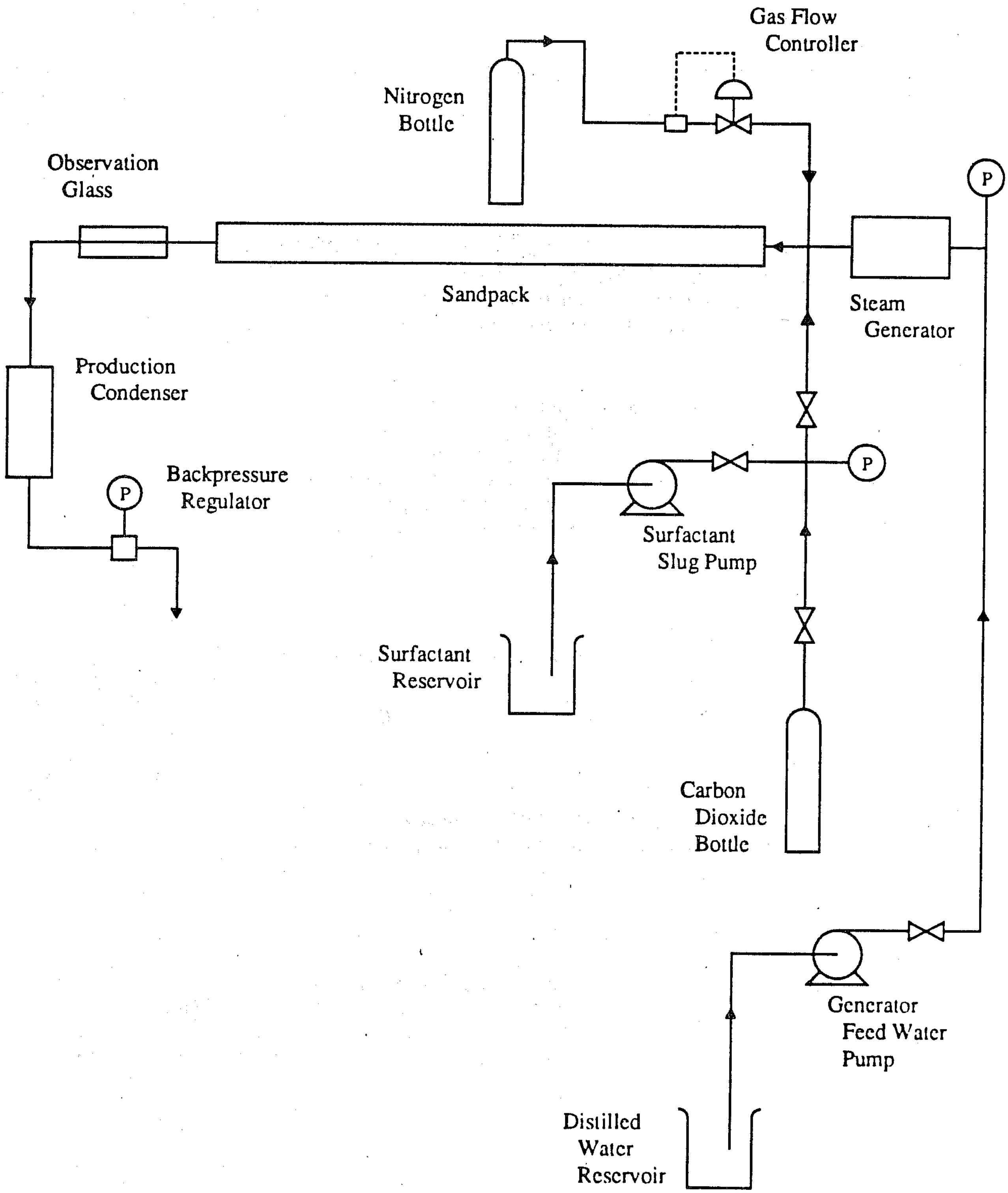

Figure 4.1 : A Simplified Representation of the Experimental Apparatus

A mass flow controller is used to control the injection rate of the nitrogen. The controller is protected by a valve that prevents backflow of the liquid or steam from the sandpack.

The three lines from the steam generator, surfactant injection system and the nitrogen supply mix at a point just upstream from the sandpack inlet. The three components then enter the sandpack at a single port in the centre of the sandpack's upstream end-plate.

4.1.3. Production System

Upon leaving the sandpack the effluent fluids pass through a section of glass tubing. This glass section permits the flow regime within the outlet line to be observed directly. If foam is being generated within the sandpack and if it is being produced it may be observed at this location. The effluent fluids then pass through a condenser which cools and condenses the steam.

The downstream sandpack pressure is controlled using a diaphragm-type back pressure regulator. Once set this regulator will usually be able to maintain the pressure constant. However, on those occasions when foam is being produced, the regulator can not adequately control the pressure. A manual system is then used, wherein the operator manually opens and closes a gate valve, directly venting the foam to atmospheric pressure. Unfortunately this method of control sometimes results in sudden severe fluctuations at the downstream end of the tube.

4.1.4. Data Acquisition

The sandpack temperature is measured by using twenty-one type-J (copper-nickel) thermocouples distributed along the length of the tube. The locations of the thermocouples are shown in Figure 4.2. Additional type-J thermocouples are used to measure the temperatures at the following locations:

- steam generator outlet line
- sandpack feed line just upstream of the sandpack
- sandpack effluent line between the glass view port and the condenser
- surfactant reservoir.

A reference thermocouple is located in an ice bath.

Pressure gradients within the pack are determined using pressures measured at five tappings, that divide the tube into four sections. Tappings are located at each end of the tube and at three intermediate locations, 16 in (0.406 m), 32 in (0.813 m), and 52 in (1.321 m) downstream from the sandpack inlet. Two pressure transducers are connected in parallel to each section to accurately measure the pressure drop across each section. The transducers have ranges of 0-10 psi (0-69 kPa) and 0-100 psi (0-690 kPa). An additional 0-100 psi (0-690 kPa) transducer is used to monitor the downstream sandpack pressure.

Five thin film heat flux sensors are applied to the outside of the sandpack tube beneath the insulation to measure the rate of heat loss from the tube to its surroundings. This information allows an estimate to be made of how closely to adiabatic the system operates. The heat flux information also allows a study to be performed of the heat transfer mechanisms operating within the sandpack. One sensor is located on the tube's upper surface a distance 38 in (0.965 m) from the inlet. The other four sensors are distributed about the tube's surface 25½ in

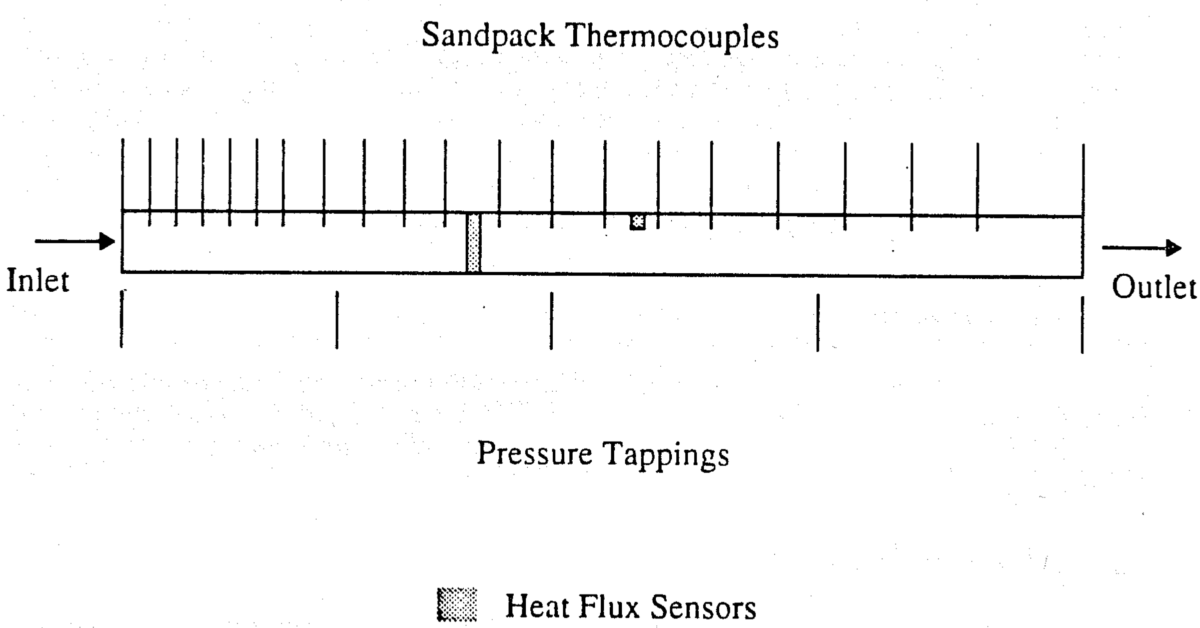

Figure 4.2 : Sandpack Instrumentation

(0.651 m) from the inlet. Of these four sensors, one is located at the top of the horizontal tube, another on the underside and the other two on one side. Each sensor has a flux-sensitive area measuring 0.55 inches by 0.71 inches (14 mm by 18 mm). The sensors are oriented so that their longer edges are parallel with the tube axis. As a consequence, the flux-sensitive area of each sensor subtends an angle of 14° on the tube's surface as measured at its axis. Each sensor also contains a type-T (copper-constantan) thermocouple which may be used to measure the sensor temperature. The presence of the sensor between the tube surface and the insulation disturbs the flow of heat through the region in the vicinity of the sensor. Corrections may be made for these disturbances (Shallcross and Wood, 1986) but for the present study such disturbances are assumed to be negligible.

All the system thermocouples, pressure transducers and heat flux sensors are connected to a Hewlett-Packard data acquisition system. This system is controlled by an IBM personal computer. Once a minute the computer instructs the data logger to scan 49 channels. The logged data is then stored on the computer's fixed disk for later analysis. Because the signals generated by the heat flux sensors are relatively noisy twenty readings are made per sensor per data set. The readings for each sensor are then averaged, and this average value is stored on the fixed disk. Several seconds are required to scan all the data channels. The pressure transducers are also connected to two chart recorders as a backup to the data stored on the computer. In one instance these chart records were used to reconstruct the pressure data when the logged experimental data was lost by the computer.

4.2. EXPERIMENTAL PROCEDURE

Prior to each experiment the required concentrations of each surfactant solution are carefully prepared. A start-up procedure is then followed. Once steam breakthrough and steady state have been achieved injection of the surfactant slugs begins. Depending upon the foam-forming ability of the surfactant, up to four surfactant slugs may be injected during a single experiment. The apparatus is then shutdown and the sandpack thoroughly cleaned, ready for the next experiment. These procedures are described in more detail in the following sections.

4.2.1. Solution Preparation Procedure

All surfactant solutions are prepared from the stock samples supplied by the manufacturers. As required, aqueous solutions of 0.10, 0.25, 0.50 and 1.0 weight percent active matter are prepared using distilled water. All surfactant solutions are prepared with 1.00 weight percent sodium chloride.

In most cases the solutions could be prepared at room temperature, however the solutions of Chevron's Chaser SD1020 and Shell's Enordet AOS1618 and AOS2024 had to be prepared at slightly higher temperatures. For those surfactants, the solutions were prepared using 50°C distilled water to ensure that the surfactants did not separate into two phases. Once prepared, the solutions of these surfactants were maintained at around 50°C until injection into the sandpack.

4.2.2. Start-Up (Steamflood) Procedure

Prior to beginning an experiment, all pressure transducers are zeroed and calibrated against an accurate Heise pressure gauge. The system is checked for leaks and the data system turned on.

Initially the sandpack is saturated with distilled water, free from any gas. The back pressure regulator is then set to the desired level, usually 70 psig (580 kPa), and the system is pressured to that level by using the surfactant injection system to inject distilled water at a rate of 4.0 ml/min. Concurrently, power to the steam generator is gradually increased while distilled water is passed through it at a rate of 4.0 ml/min. Whilst the furnace is coming to temperature the steam generator effluent is purged through a condenser. Once the furnace is at temperature the purge line is closed, causing the pressure in the steam line to increase to the desired sandpack operating pressure. When this is achieved steam injection into the sandpack is begun. Simultaneously, injection of the cold distilled water into the sandpack through the surfactant injection line is stopped.

Slightly superheated steam is injected into the sandpack at a rate of 4.0 ml/min, cold water equivalent. At a back pressure of 70 psig (580 kPa), the steam front typically takes about three hours to traverse the length of the sandpack. The advance of the steam front is monitored using the sandpack thermocouples, pressure transducers and heat flux sensors.

Thirty minutes after steam breakthrough has been observed nitrogen injection is begun. The nitrogen is injected into the sandpack at a rate of 0.081 l/min, equivalent to a 0.05 mole fraction in the gas phase. Nitrogen breakthrough is usually observed seventy seconds after injection begins.

4.2.3. Surfactant Injection Procedure

Steam foam experiments involve the injection of the surfactant solution either continuously or as a series of discrete slugs. The use of discrete slugs of a finite duration allows the study of transient phenomena such as foam persistence. Up to four slugs of the same surfactant, but at possibly different concentrations, may be injected into the sandpack during a single experiment. The volume of each slug is equivalent to ten percent of the sandpack's pore volume. At an injection rate of 4.0 ml/min, a 35½ minute period is required to inject each slug. During this period injection of both steam and nitrogen continues at their earlier rates. The first slug is not injected until at least one hour after nitrogen breakthrough is achieved. This is to ensure that the system is at steady state. Prior to the injection of each surfactant slug the surfactant injection system including the surfactant pump and injection lined are primed and pressured to the sandpack pressure using the surfactant solution. Pressuring the injection lines prevents the sandpack fluids from backflowing along the injection line when the valves are opened.

For most surfactants, the concentration of the first surfactant slug is 0.1 weight percent. During, and for one hour after injection of the slug, the pressures within the sandpack are closely monitored. Generation of foam within the sandpack is indicated by an increase in the pressure gradients observed within the pack. Production of foam from the tube may be observed using the sight-glass connected to the outlet line. If, after one hour after injection of the slug has stopped, there is no indication of foam formation then a second surfactant slug is injected at the higher concentration of 0.25 weight percent. The surfactant concentration is progressively increased to 0.50 and finally 1.00 weight percent in succeeding slugs until a response is observed. When a response is noted, the slug producing that response is followed by one or more slugs of the same concentration. Succeeding slugs are not injected until at least one hour has passed since the response to the preceding slug has diminished. On occasion the injection of a slug at the minimum foaming concentration will not be followed by a second slug if the response to the first slug increased the pressure in the sandpack to near the operational safety limit. A flowchart showing the slug injection procedure followed in most of the experiments is presented in Fig. 4.3.

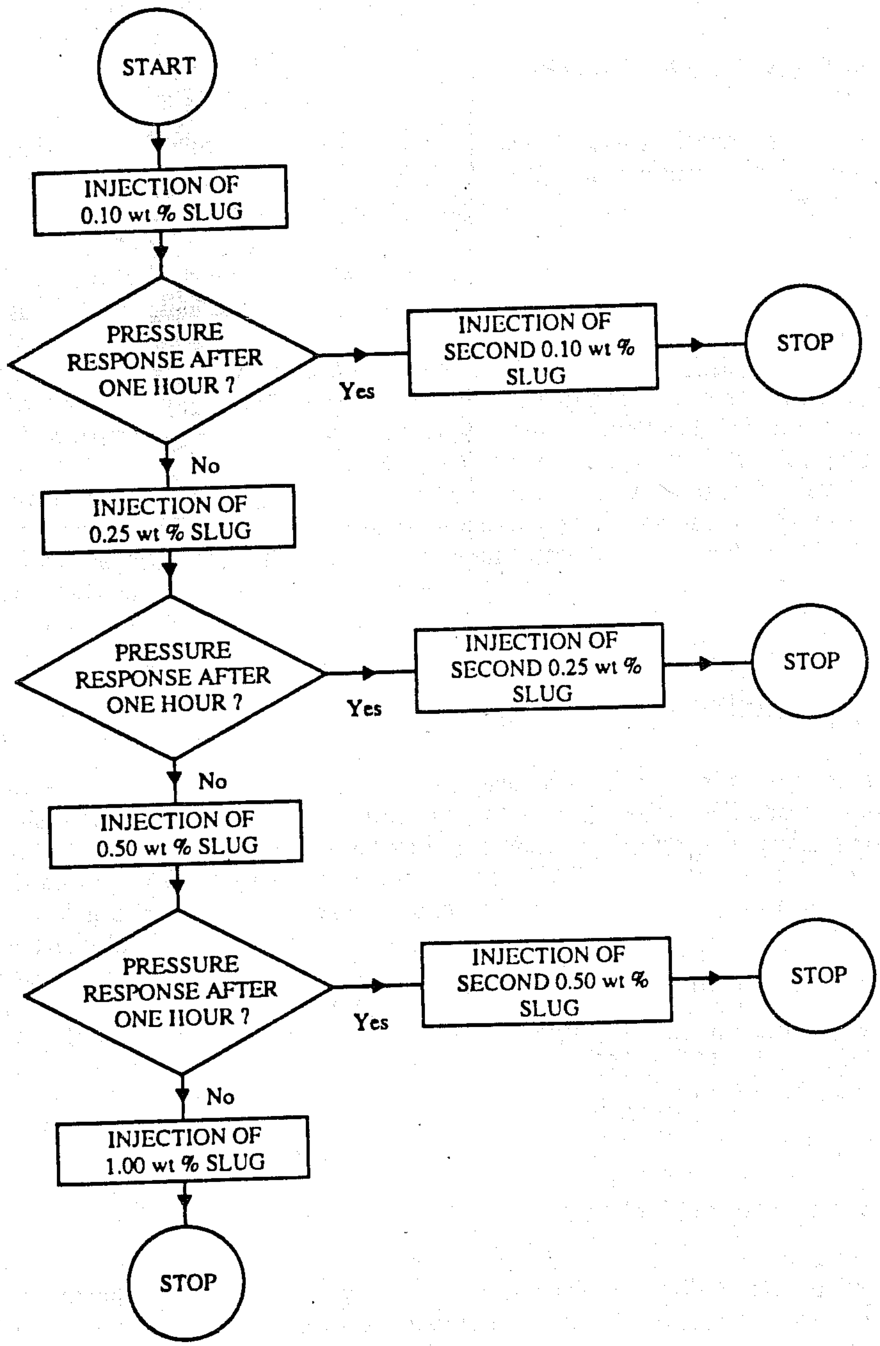

Figure 4.3 : Flowsheet of Experimental Procedure

All pressure transducers with the exception of the back pressure transducers are calibrated after the injection of every surfactant slug whether a pressure response is illicited or not.

4.2.4. Sandpack Cleaning Procedure

The same sandpack is used to test all surfactants so that their foam-forming abilities may be compared on a common basis. It is therefore vital that the sandpack be thoroughly cleaned after each experiment to remove all surfactant traces.

Immediately following the completion of each experiment, the injection of steam and nitrogen is stopped. A minimum of ten litres of cold distilled water is then used to rinse and cool the sandpack. At least 750 ml (roughly half a sandpack pore volume) of isopropanol is then injected at a rate of 10 ml/min. The isopropanol is used to clean the surfactant from the pump, injection system and sandpack. This is followed by at least 15 litres of distilled water injected at a rate of 65 ml/min. This slug of water washes the isopropanol from the system. Carbon dioxide is then injected into the sandpack to remove all traces of nitrogen. Finally, at least ten litres of distilled water is injected at 65 ml/min in order to remove all the carbon dioxide. At the conclusion of the procedure at least 50 litres (35 sandpack pore volumes) of distilled water will have been injected through the sandpack. The pack is then isolated from the rest of the equipment, ready for the next experiment. This procedure, which typically takes at least one day to complete, leaves the sandpack saturated with water and free of gas.

4.3. SURFACTANTS

The foam-forming ability of seventeen different surfactants were tested in the one-dimensional sandpack model. These surfactants included both commercially-available and experimental samples supplied by Chevron, Hoechst and Shell. In particular Chevron's Chaser SD1000 and Shell's Enordet AOS1618 have been successfully deployed in the field to generate steam foam as noted in Chapter 2. Surfactants representing the following four chemical structures were studied: alpha-olefin sulphonates (AOS), internal olefin sulphonates (IOS), linear toluene sulphonates (LTS) and linear xylene sulphonates (LXS). Surfactants of similar chemical structures but having different alkyl chain lengths were also studied. As an example, the alkyl chains of the alpha-olefin sulphonate surfactant AOS1618 contains either 16 or 18 carbon atoms, whereas the alkyl chains in the AOS2024 surfactant contain 20, 22 or 24 carbon atoms. The chemical structures of the surfactants studied in this investigation are summarized in Table 4.2.

4.4. EXPERIMENTAL DESIGN

A total of twenty-eight experimental runs were performed during the course of the experimental program. A summary of the experimental program is presented in Table 4.3. To test the importance of the presence of a non-condensible gas upon foam stability, one experiment (Run 25) was performed without nitrogen injection. Two experiments were also performed at different back pressures (Runs 31 and 32). Also, some portions of various experiments were repeated to test the experimental reproducibility. A summary of the experimental conditions is presented in Table 4.4.

Table 4.2 : Summary of Surfactants Tested

Surfactant	Manufacturer	Chemical Structure
Chaser SD1000	Chevron	dimerized alpha-olefin sulphonate
Chaser SD1020	Chevron	unknown
OS fl	Hoechst	unknown
SAS 60	Hoechst	unknown
Enordet AOS1416	Shell	alpha-olefin sulphonate
Enordet AOS1618	Shell	alpha-olefin sulphonate
Enordet AOS2024	Shell	alpha-olefin sulphonate
Enordet IOS1517	Shell	internal olefin sulphonate
Enordet IOS1720	Shell	internal olefin sulphonate
Enordet IOS2024	Shell	internal olefin sulphonate
Enordet LTS1618D	Shell	linear toluene sulphonate
Enordet LTS18	Shell	linear toluene sulphonate
Enordet LXS814	Shell	linear xylene sulphonate
Enordet LXS1112	Shell	linear xylene sulphonate
Enordet LXS1314	Shell	linear xylene sulphonate
Enordet LXS16	Shell	linear xylene sulphonate
Enordet LXS18	Shell	linear xylene sulphonate

Table 4.3 : Summary of Experimental Program

Experiment No.	Surfactant	Pressure (psig)	Nitrogen Injection	Slug Concentration (wt %) First	Second	Third	Fourth
6	SD1000	70	Yes	0.10	0.10	0.10	0.10
7	AOS1416	70	Yes	0.10	0.10	0.10	--
8	AOS1416	70	Yes	0.50	0.50	0.50	--
9[1]	AOS2024	70	Yes	0.10	0.10	0.10	--
10	AOS1618	70	Yes	0.10	0.10	--	--
11	IOS1720	70	Yes	0.10	0.10	0.10	--
12	LTS1618D	70	Yes	0.10	0.25	0.50	0.50
13	IOS1517	70	Yes	0.10	0.25	0.50	--
14	LXS814	70	Yes	0.10	0.25	0.50	1.00
15	SD1020	70	Yes	0.10	0.25	0.50	--
16	IOS2024	70	Yes	0.10	0.25	--	--
17	LXS18	70	Yes	0.25	0.50	1.0	--
18	OS fl	70	Yes	0.10	0.25	0.25	0.25
19	SAS60	70	Yes	0.10	0.25	0.50	--
20	LXS16	70	Yes	1.00	1.00	--	--
21	AOS2024	70	Yes	0.10	--	--	--
22	IOS1720	70	Yes	0.10	0.25	--	--
23	LTS18	70	Yes	0.10	0.10	--	--
24[2]	IOS2024	70	Yes	0.10	0.25	0.25	--
25	AOS2024	70	No	0.10	0.10	0.25	--
26	LXS16	70	Yes	1.00	--	--	--
27	LXS1314	70	Yes	1.00	--	--	--
28	LXS1112	70	Yes	1.00	1.00	--	--
29	LXS18	70	Yes	1.00	--	--	--
30	AOS1618	70	Yes	0.10	0.10	--	--
31	AOS1618	100	Yes	0.10	0.10	--	--
32	AOS1618	40	Yes	0.10	--	--	--
34	SD1020	70	Yes	0.10	0.25	0.50	1.00

1 After the experiment was complete it was found that the surfactant solution had been incorrectly prepared. All data from this run is therefore rejected.

2 Logged experimental data was lost by the computer. Data was reconstructed from chart records.

Table 4.4 : Experimental Conditions

Sandpack Properties:		
Length	1.830 m	(6.0 ft)
Average Diameter	54.8 mm	(2.16 in)
Porosity	33%	
Absolute Permeability	89.8 μm^2	(91.0D)
Pore Volume	1420 ml	(0.0502 ft^3)
Injection Conditions and Rates:		
Back pressure	580 kPa,a	(70 psig)
Steam Injection Rate	4.0 ml/min(cwe)	
Surfactant Injection Rate	4.0 ml/min	
Nitrogen Injection Rate	0.081 l/min	
Surfactant Slug Properties:		
Surfactant Concentration	0.10, 0.25, 0.50 and 1.0 wt %	
Slug Volume	142 ml	(10% sandpack pv)
Slug Injection Period	35.4 minutes	
Sodium Chloride Concentration	1.0 wt %	

5. EXPERIMENTAL RESULTS

The main experimental observations recorded during the twenty-eight successful experiments are presented in this Chapter. Data recorded prior to steam breakthrough for each run is discussed in the first section. The recorded data is used to estimate the velocity and the inclination of the steam front as it passes through the sandpack. The heat transfer mechanisms operating within the sandpack during the generation and propagation of the foam are then discussed in Section 5.2. The ability of each of the surfactants to spontaneously form foam within the sandpack under the experimental conditions may be judged from the information presented in Section 5.3. The importance of the presence of the non-condensible gas such as nitrogen is then discussed in the next section. Finally, the effect of varying the back pressure on the foam-forming ability of one surfactant is covered in Section 5.5.

5.1. STEAMFLOOD DATA

5.1.1. Steam Front Velocity

Both the sandpack thermocouples and the heat flux sensors may be used to independently estimate the velocity of the steam front as it passes along the one-dimensional model. Figure 5.1 shows the position of the steam front as a function of time for a typical 70 psig steamflood recorded using the twenty-one sandpack thermocouples. The steam front is defined as having passed a sandpack thermocouple when the temperature observed by the thermocouple is within 1°C of the maximum observed temperature at that location. From this data, the average frontal velocity may be estimated as 30.3 in/hr (1.28 cm/min). The figure clearly shows however that the steam front slows as it advances through the sandpack. This is because the advancing steam front leaves behind it an ever-increasing heat transfer area from which heat may be lost to the surroundings. In fact, if the sandpack was not so well insulated to reduce heat losses, the steam front would reach a limit beyond which it could not advance. The heat lost to the surroundings would exactly balance the heat introduced into the system in the steam. The insulation in the present system is more than adequate to ensure that this does not occur.

The data collected using the heat flux sensors may also be used to estimate the velocity. Figure 5.2 shows the heat fluxes recorded by the two sensors located on top of the tube 25½ inches (0.651 m) and 38 inches (0.965 m) from the tube inlet during a 70 psig steam flood. The peak in the heat flux recorded by the upstream sensor occurred at 0.858 hours while the downstream sensor flux peaked at 1.274 hours. Thus the average steam velocity between these two locations may be estimated as 30.0 in/hr (1.27 cm/min). As the flux data was recorded at intervals of 40 seconds the error associated with this estimate is 1.6 in/hr (0.07 cm/min). This agrees closely with the first velocity estimate.

Figure 5.3 compares the frontal positions for the three steam floods conducted against different system back pressure. The rate at which the steam front advances slows with increasing pressure, because the increased steam saturation temperature associated with the increased pressure results in higher heat losses to the surroundings. The average heat flux recorded by the five sensors following steam breakthrough was 187 W/m^2 for a typical 70 psig steam flood, 164 W/m^2 for the 40 psig steam flood and 202 W/m^2 for the 100 psig steam flood.

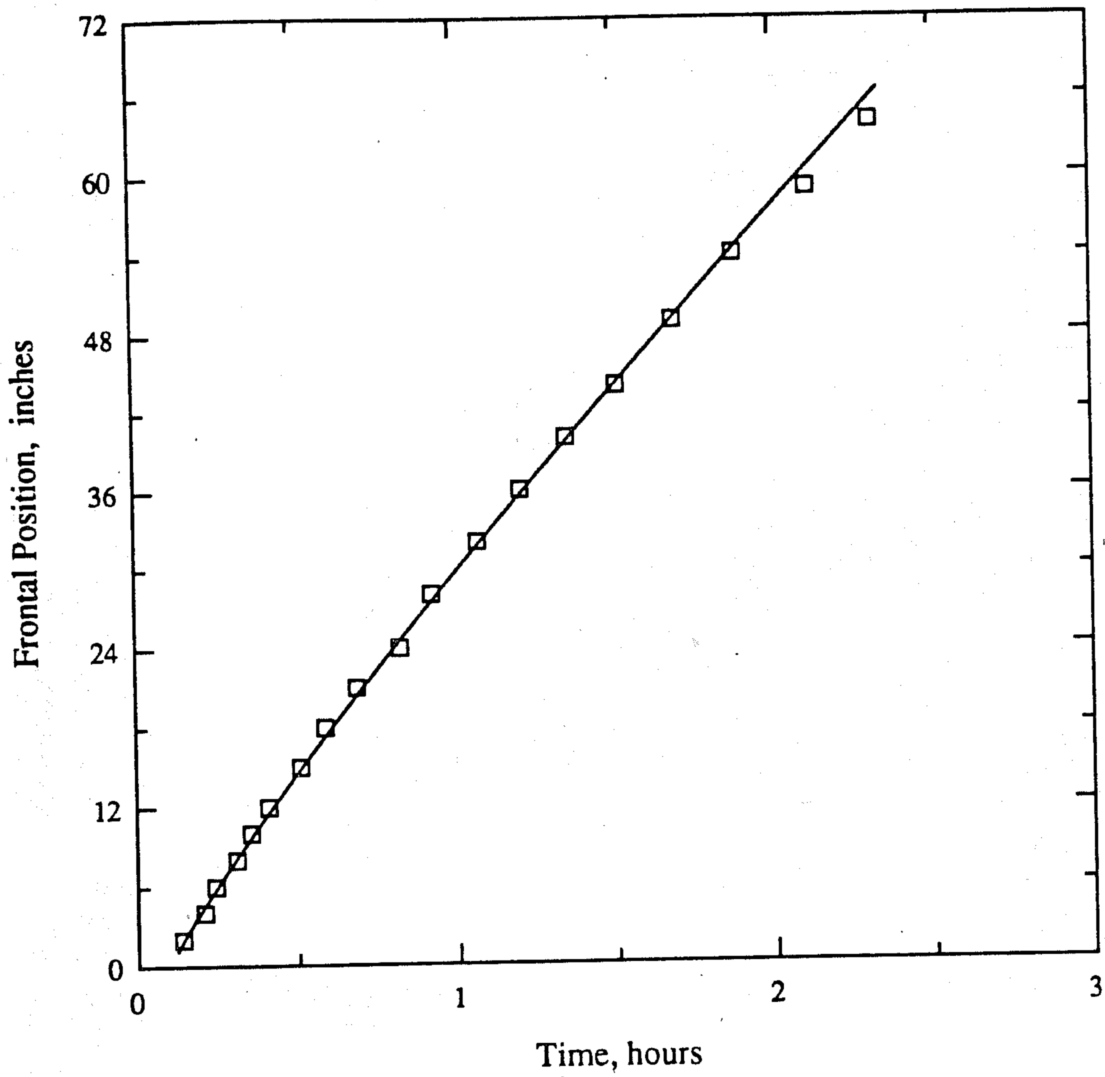

Figure 5.1 : Steam Front Position for 70 psig Steam Flood

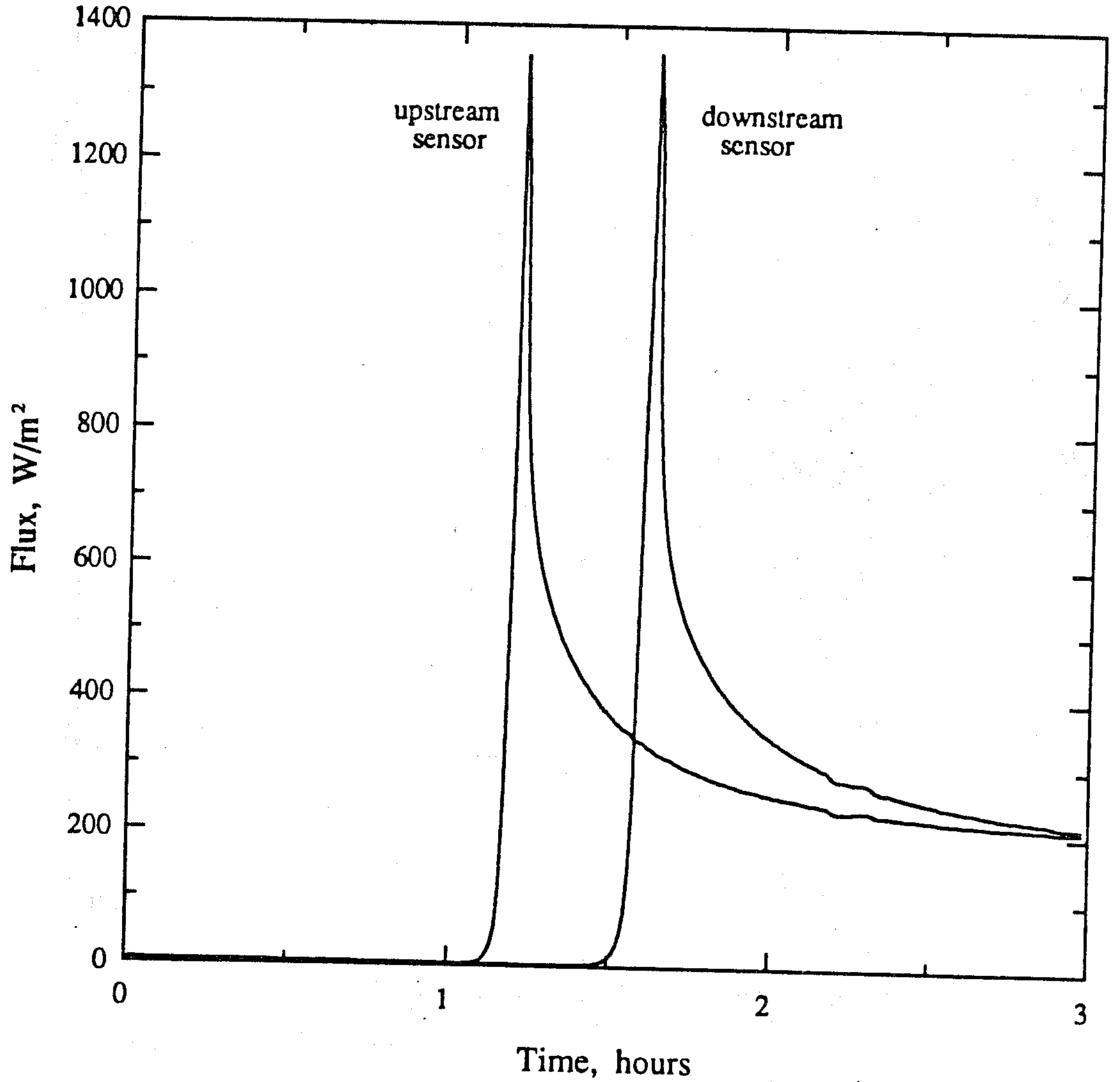

Figure 5.2 : Comparison of Heat Fluxes Measured by Top, Upstream and Downstream Sensors during a 70 psig Steamflood

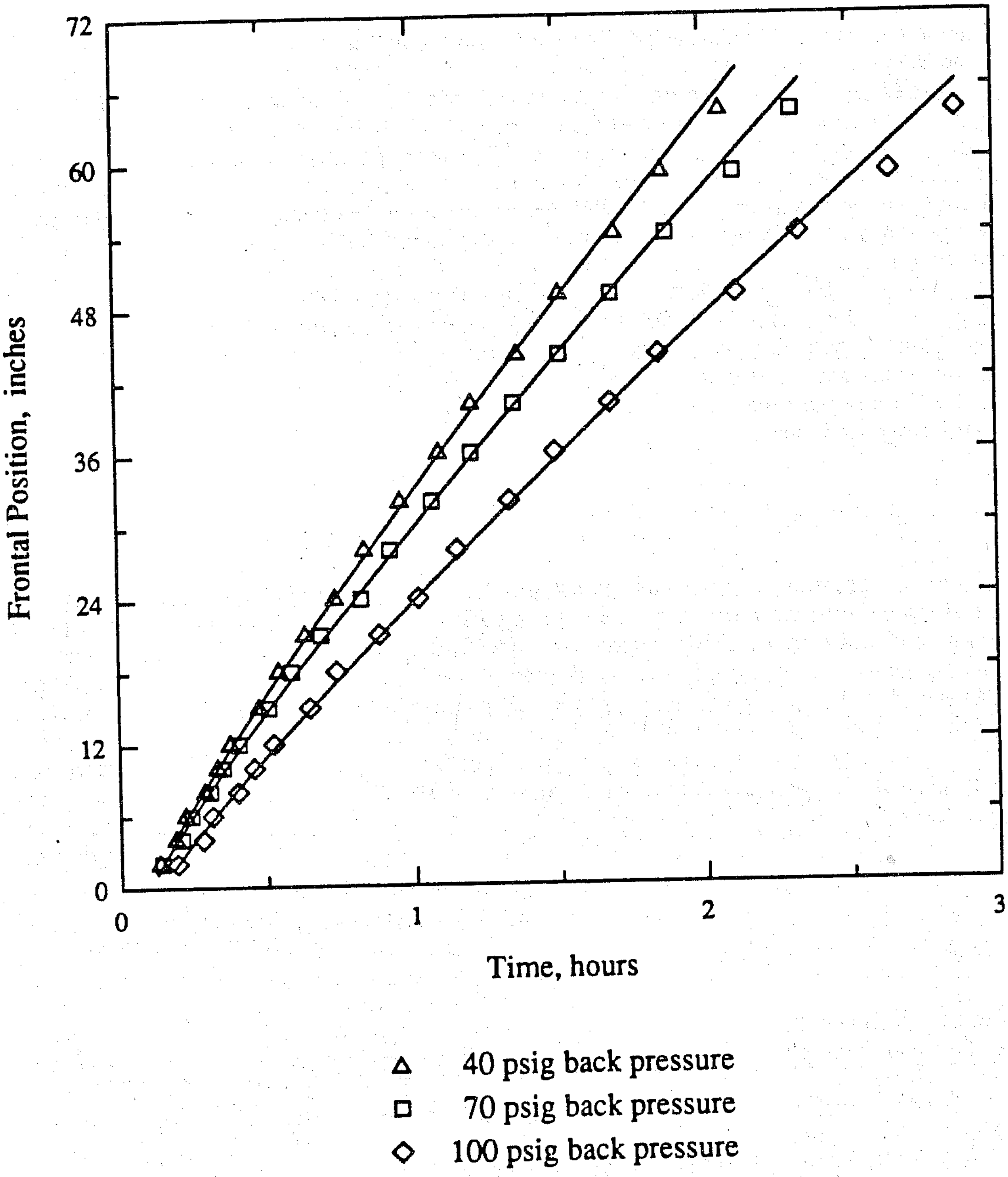

Figure 5.3 : Steam Front Position for Three Different Back Pressures

5.1.2. Steam Front Inclination

The steam front's inclination may be estimated using the flux data recored by the four sensors located 25½ inches from the tube inlet. Figure 5.4 shows the variations in the heat fluxes recorded by the four sensors as the steam front passed their location. The diagram clearly shows that the steam front passed the upper sensor before it passed the lower sensors, indicating that it was inclined from the vertical. The steam front passed the upper, side sensor located 61° below the top of the horizontal tube, 1.35 minutes after passing the top sensor; passed the lower, side sensor located 131½° below the top of the tube, 3.71 minutes after passing the top sensor; and passed the lowermost sensor (180° below the top of the tube), 4.05 minutes after passing the top sensor. Knowing the average steam front velocity, 30.0 in/hr, and the diameter of the sandpack, 2.16 in (5.49 cm), the steam front is estimated to be inclined 43° from the vertical. This suggests that gravity override is occurring within the supposedly one-dimensional sandpack model. Again, because the flux data was recorded at intervals of 40 seconds the error associated with the estimate gives a range of values for the inclination of 30° to 53°. Decreasing the time interval between measuring the flux data would increase the accuracy of the calculated values.

5.1.3. Sandpack Temperatures

Figure 5.5 presents a three-dimensional plot of sandpack temperature against time and distance along the tube from the inlet. Prior to injection of the steam the sandpack temperature is constant and uniform at 20°C (region A). The exception to this is the region near the upstream flange where the temperature is slightly elevated (B) due to the presence of a band heater around that flange. Once steam injection commences, the steam front begins to advance through the sandpack. At a time of 2 hours, the steam front has advanced to point C, while ahead of the front (D) the sandpack is at its pre-injection temperature. Behind the front (E), the sandpack is at the steam saturation temperature of 158°C (316°F). Eventually the sandpack will be completely at 158°C (F) with the exception of the region (G) near the heated upstream flange. The apparent elevated temperature at point H is probably due to an inaccurate thermocouple.

5.1.4. Steam Flood Heat Losses

Figure 5.6 shows the variation in the heat flux recorded during the 70 psig steam flood by the top, upstream heat flux sensor. The variation in the temperature recorded by the same sensor over the same period is presented in Figure 5.7. Before the steam front passed the sensor location there was virtually no flow of heat from the sandpack to the surrounding insulation: the sandpack was in thermal equilibrium with the insulation. At about 0.78 hours a slight increase was detected in the measured heat flux as the steam front advanced nearer to the sensor's location. The flux peaked at a maximum of 1358 W/m^2 at 0.86 hours as the steam front passed the sensor. The passing of the front was also indicated by the step-like increase in the sensor's temperature. The flux peak occurred when the temperature difference between the hot tube wall and the cooler insulation material was a maximum. As time passed the insulation temperature gradually increase while the tube wall temperature remained essentially constant, very close to the steam saturation temperature. As a result the heat flux decayed towards a steady state limit of 187 W/m^2 for the 70 psig steam flood.

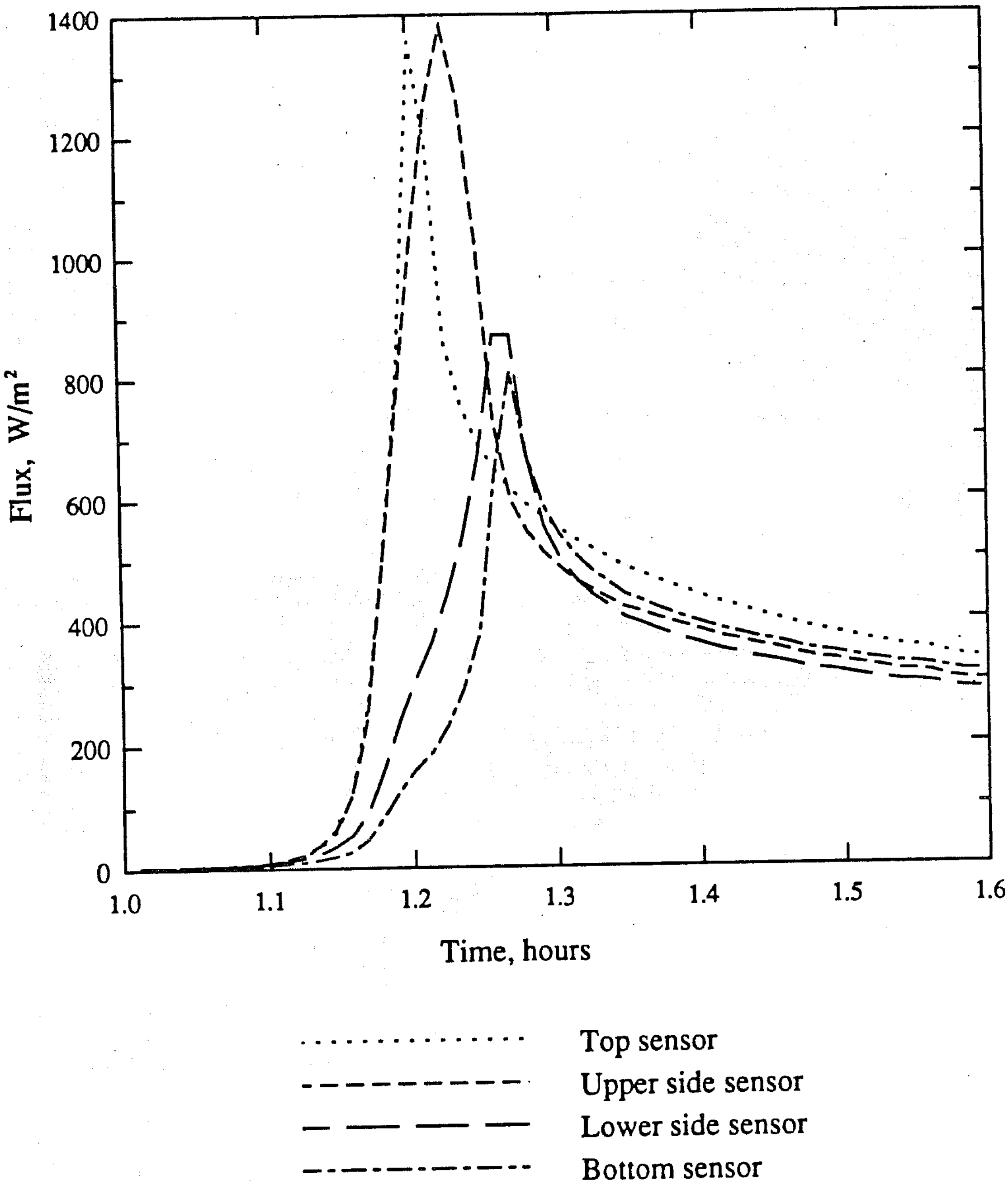

Figure 5.4 : Heat Fluxes Measured by the Four Sensors Located 25½ inches from the Tube Inlet during a 70 psig Steamflood

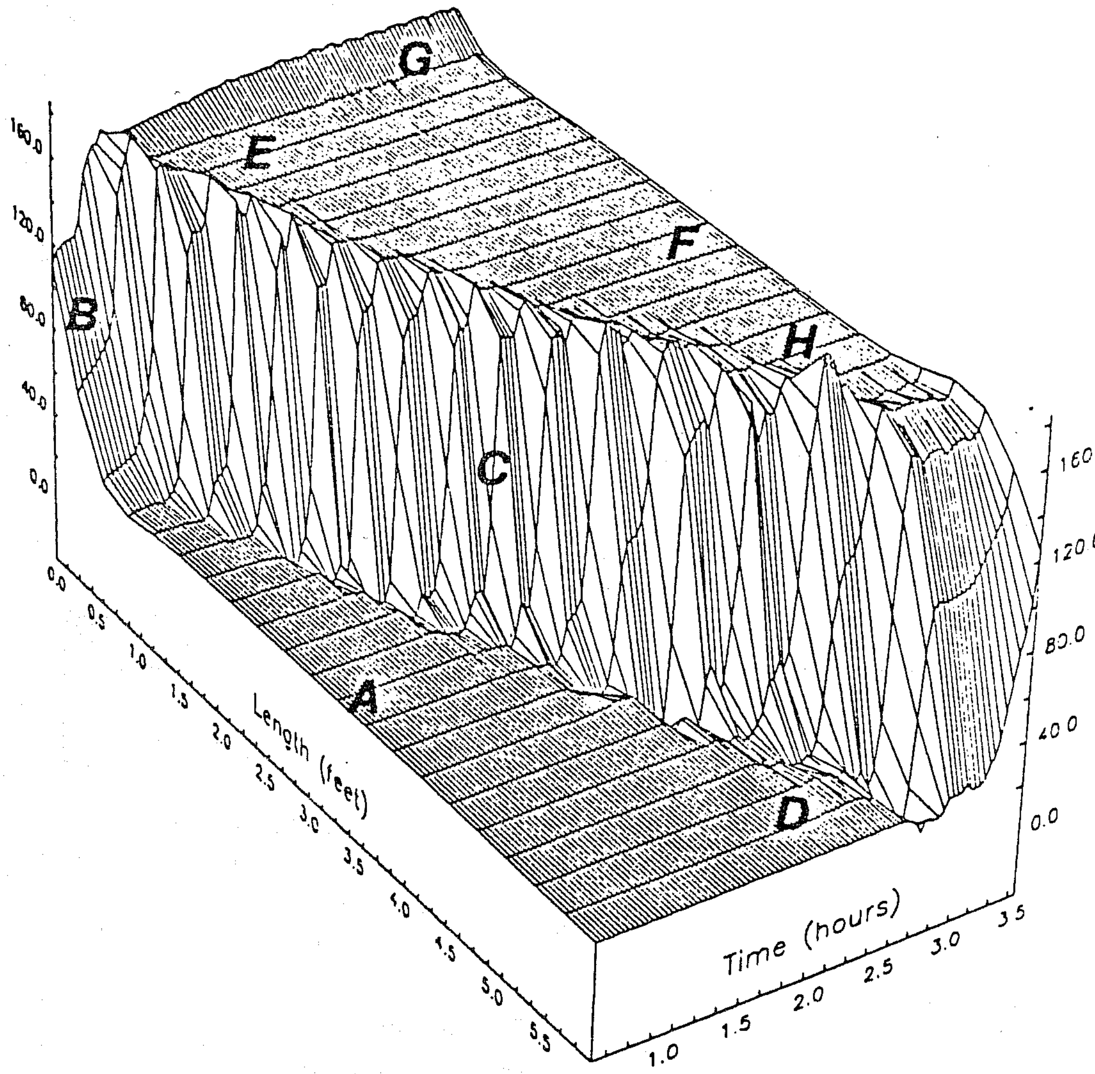

Figure 5.5 : Sandpack Temperatures during a Typical Steamflood

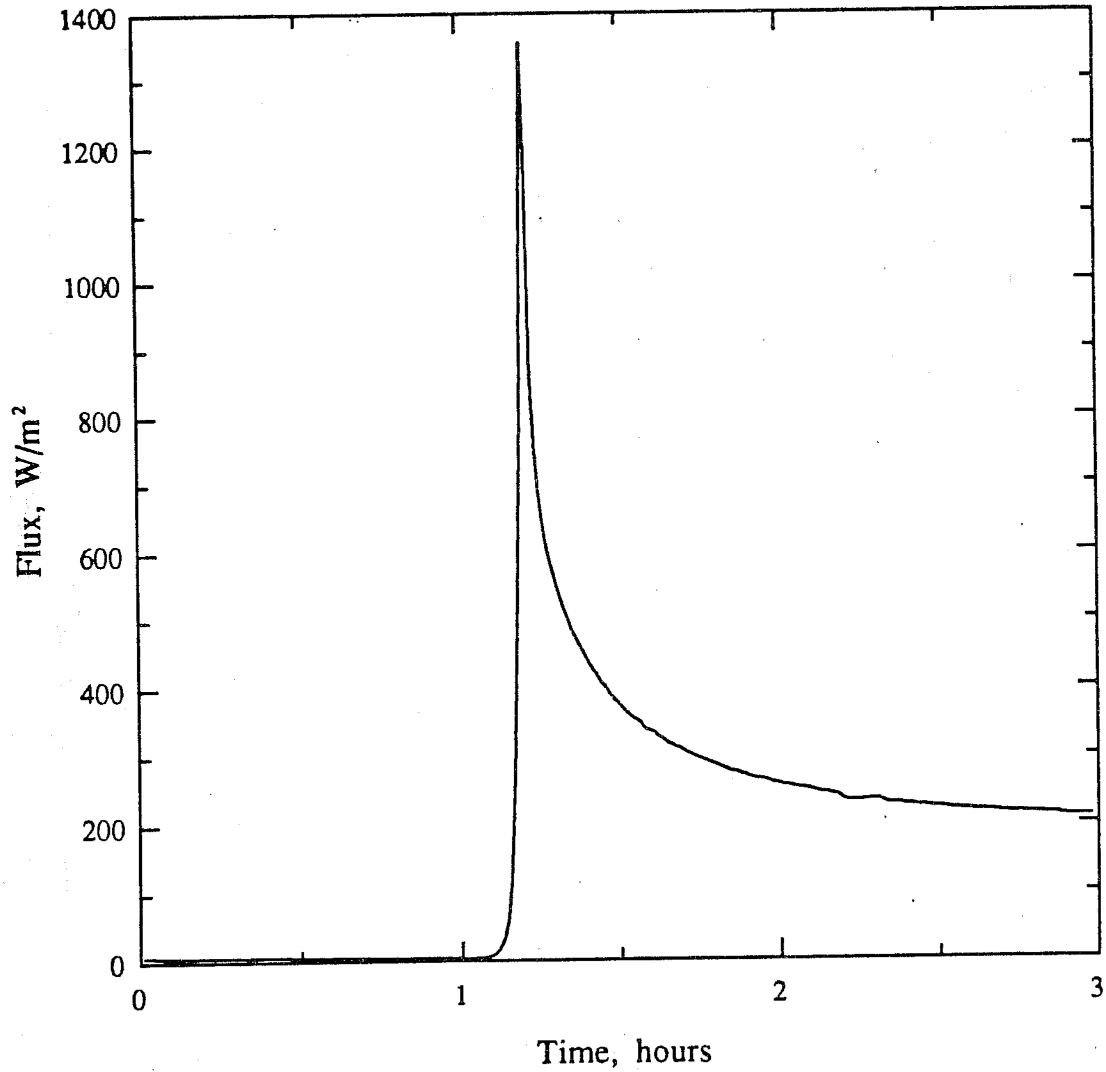

Figure 5.6 : Heat Flux at Exterior Sandpack Wall Measured Using the Top, Upstream Sensor during 70 psig Steamflood

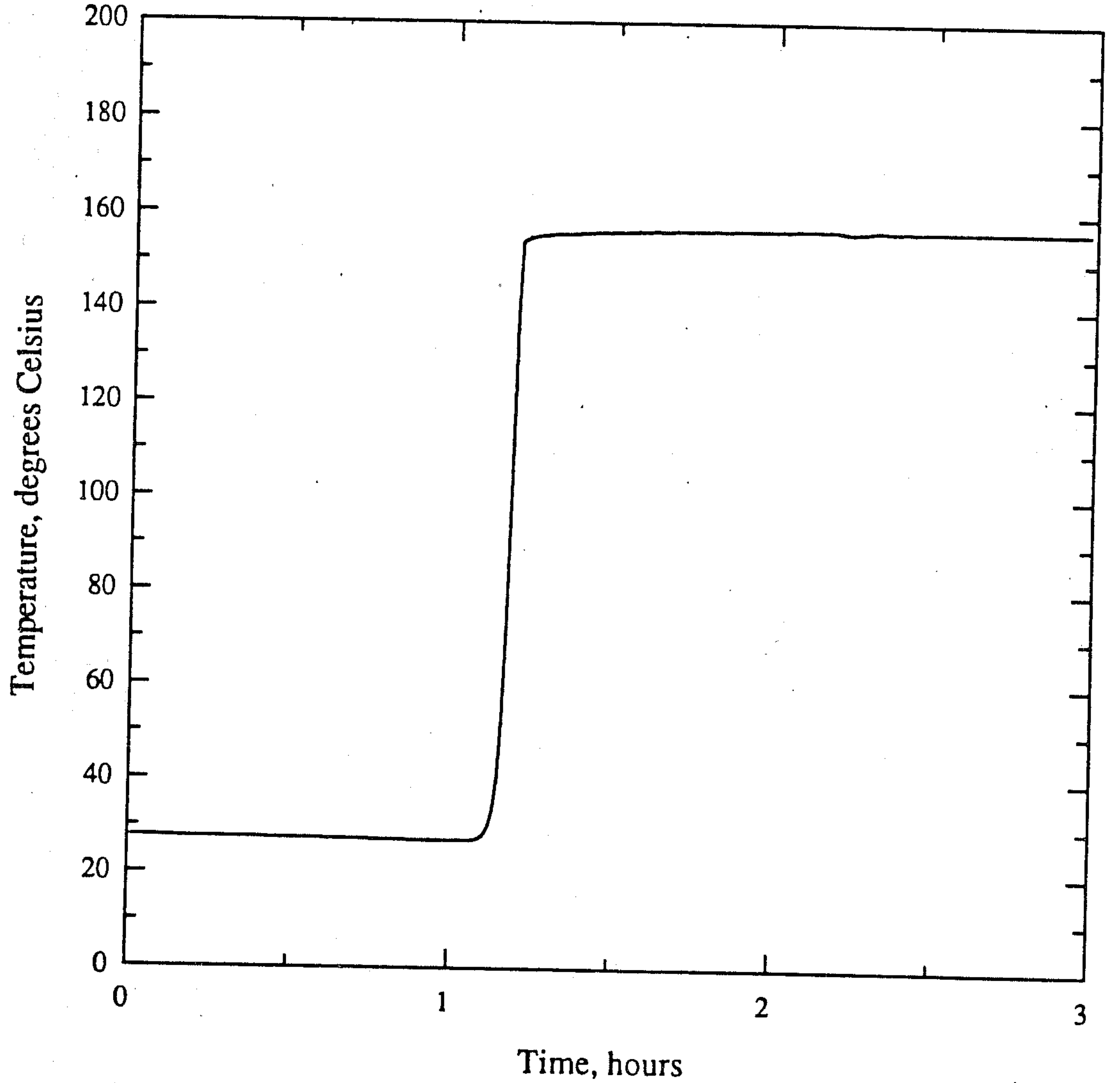

Figure 5.7 : Temperature of Top, Upstream Sensor during 70 psig Steamflood

5.1.5. Steady State Outlet Steam Quality

During the steam floods slightly superheated steam was injected into the sandpack. However, because of the heat losses from the sandpack to the surroundings, some of the steam condensed, resulting in a reduction in the quality of the steam produced after steam breakthrough. Using both a simple energy balance and a knowledge of the steady state rate of heat losses from the sandpack estimates may be made for the quality of steam that was produced after steam breakthrough.

To illustrate the method used, consider the observations made during the 70 psig steam flood. At 3.7 hours, superheated steam at 177°C was being injected into the system against a back pressure of 70.7 psig (589 kPa). At this pressure, the steam saturation temperature is 158.0°C, the specific enthalpy of saturated water is 667 kJ/kg, the specific enthalpy of saturated steam is 2756 kJ/kg, and the latent heat of vapourization is 2089 kJ/kg (Mayhew and Rogers, 1977). Also, at 70.7 psig, the specific heat of steam between 158.0°C and 177.0°C is about 2.253 kJ/kg°C (Weast and Astle, 1981). Thus, the specific enthalpy of superheated steam at 70.7 psig and 177.0°C, $\hat{H}_{steam,in}$, is given by

$$\hat{H}_{steam,in} = 2756 \text{ kJ/kg} + (177.0°\text{C} - 158.0°\text{C}) \times 2.253 \text{ kJ/kg°C} = 2799 \text{ kJ/kg}$$

Distilled water is supplied to the steam generator at 20°C at a rate of 4.0 ml/min. Assuming the density of the water is 1000 kg/m^3, this is equivalent to a mass flowrate, $\dot{m}$, of 6.67×10^{-5} kg/s.

The average steady state heat flux measured by the five sensors is 187 W/m^2. Taken over the entire external surface of the tube, this results in a heat loss to the surroundings of 61.3 W.

A simple energy balance over the sandpack may be written as:

$$\begin{Bmatrix}\text{Heat Injected}\\ \text{with Steam}\end{Bmatrix} = \begin{Bmatrix}\text{Heat Produced}\\ \text{with Steam}\end{Bmatrix} + \begin{Bmatrix}\text{Heat Lost to}\\ \text{Surroundings}\end{Bmatrix}$$

Thus,

$$\hat{H}_{steam,out} = \hat{H}_{steam,in} - \frac{Q}{\dot{m}}$$

$$= (2799 \times 10^3 \text{ J/kg}) - \frac{(61.3 \text{ W})}{(6.67 \times 10^{-5} \text{ kg/s})} = 1880 \text{ kJ/kg}$$

Thus, $\text{steam quality} = \frac{(1880 \text{ kJ/kg}) - (667 \text{ kJ/kg})}{(2089 \text{ kJ/kg})} \times 100$

$$= 58.1\ \%$$

This result suggests that a significant proportion of the injected steam condenses within the sandpack due to the heat losses to the surroundings. Similar steam quality calculations performed for the other experiments suggest that the quality of the steam produced decreases with increasing pressure: during the 40 psig steam flood 63.4 percent quality steam is calculated as being produced from the recorded data, while the quality falls to 52.2 percent for the 100 psig steam flood.

5.2. CONSIDERATIONS IN INTERPRETING PRESSURE RESPONSE DATA

A thorough understanding of the heat transfer mechanisms operating within the sandpack during the generation and propagation of the foam is essential if the experimental observations are to be correctly interpreted. This is clearly demonstrated in the following sections.

5.2.1. Sandpack Temperature and Pressure Profiles

The twenty-one thermocouples distributed along the length of the one-dimensional model may be used to monitor the sandpack temperature distributions during the periods of surfactant injection and subsequent foaming. Figure 5.8 presents two views of the same three-dimensional plot showing the variation in sandpack temperature with both time and distance from the sandpack inlet. The data was taken during Run 30 which involving the injection of two 0.10 wt % slugs of Shell's Enordet AOS 1618 into the pack against a back pressure of 70 psig.

The diagram clearly shows that before injection of the first surfactant slug the temperature within the sandpack was constant and uniform at the steam saturation temperature (Region A in the diagram). The exception to this was in the region near the inlet where the temperature was slightly elevated (B) due to the presence of an active band heater on the upstream flange. Immediately following the beginning of surfactant injection the temperature at the upstream flange dropped sharply (C). This was because the average specific enthalpy of the injected fluids was decreased by the sudden addition of the cold liquid surfactant slug to the injected steam. As foam was spontaneously generated within the pack near the inlet, an increase was noted in the pressure drop across the first section of the model. As shown in Figure 5.9, this increase is clearly evident just 10 minutes after surfactant injection was begun. Since the saturation temperature of the steam increases with increasing pressure, an increase in the sandpack temperature near the inlet (D) is associated with the generation of foam.

While foam was forming in the sandpack near the inlet a drop in the sandpack temperature downstream was observed (E). This decrease in the sandpack temperature ahead of the steam foam front was caused by a decrease in the partial pressure of the steam. When the liquid surfactant solution was added to the superheated steam, some of the steam was condensed to heat the liquid to the steam temperature. Whereas prior to injection of the surfactant the vapour phase was approximately 95 vol % steam with the balance nitrogen, as slug injection began the steam content in the vapour phase decreased to approximately 87 vol %. The associated decrease in the steam partial pressure resulted in an immediate decrease in the steam saturation temperature from 156°C to around 154°C. As the injection pressure increased in response to the generation of foam, the quality of the injected steam decreased further. This is because the heater used to generate the steam supplied heat at a constant rate, independent of the injection pressure. The increase in injection pressure was accompanied by a further decrease in the steam saturation temperature associated with the falling off of the partial pressure of the steam. Heat losses from the downstream sections of the model caused the temperature of the sandpack to fall with the steam saturation temperature.

Twenty minutes following commencement of surfactant injection the foam had propagated well into the pack. Foaming was strongest in the second sandpack section (Figure 5.9) while in the first the foam had essentially collapsed. At this time the sandpack temperature was essentially uniform throughout the first section (Region F in Figure 5.8). An hour after surfactant injection began the foam collapsed rapidly throughout the model (G and H), restoring the sandpack temperatures to their pre-injection values (I). More than an hour later

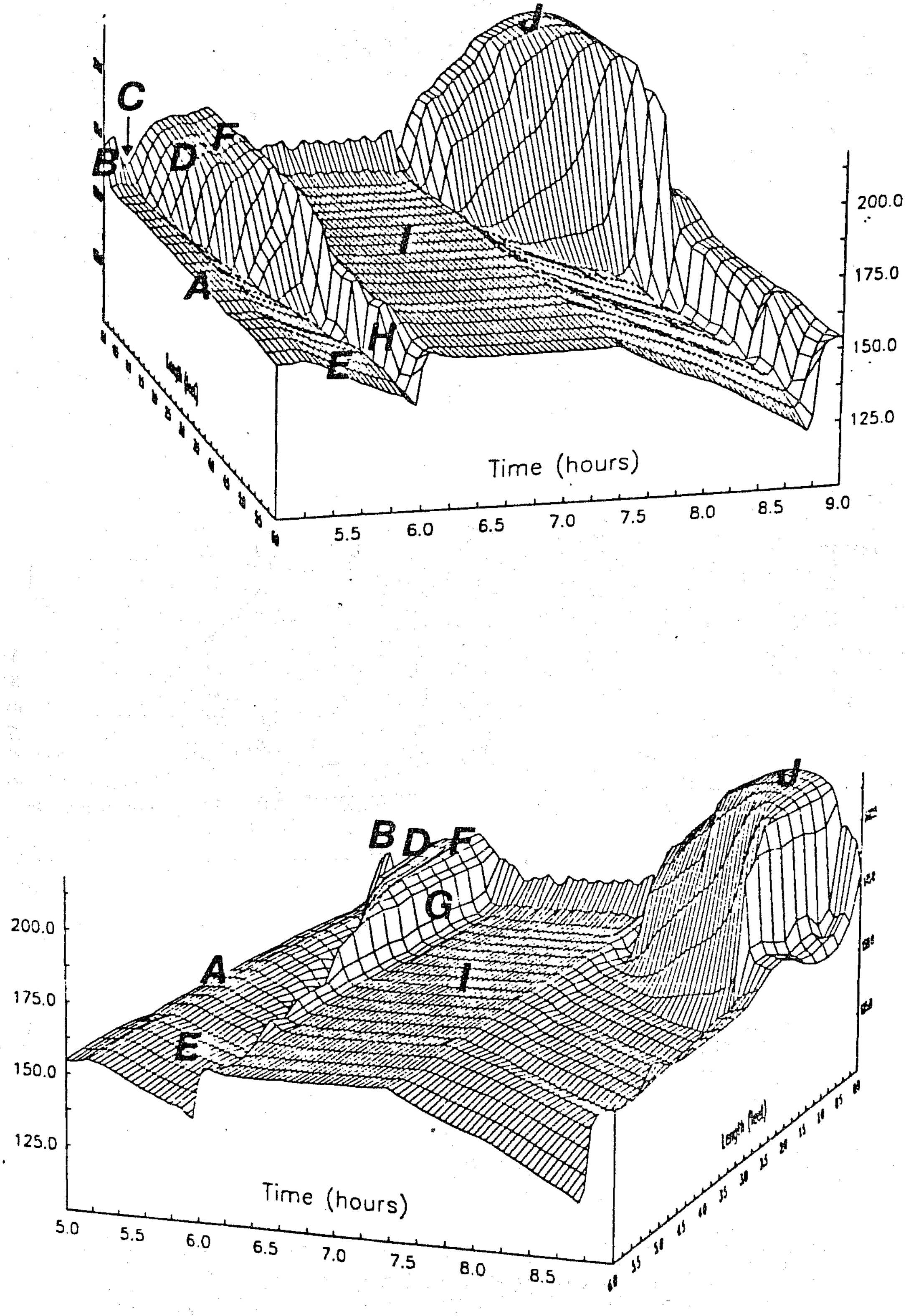

Figure 5.8 : Two Views of the Sandpack Temperature Response to Injection of Two 0.10 wt % Slugs of Shell Enordet AOS 1618

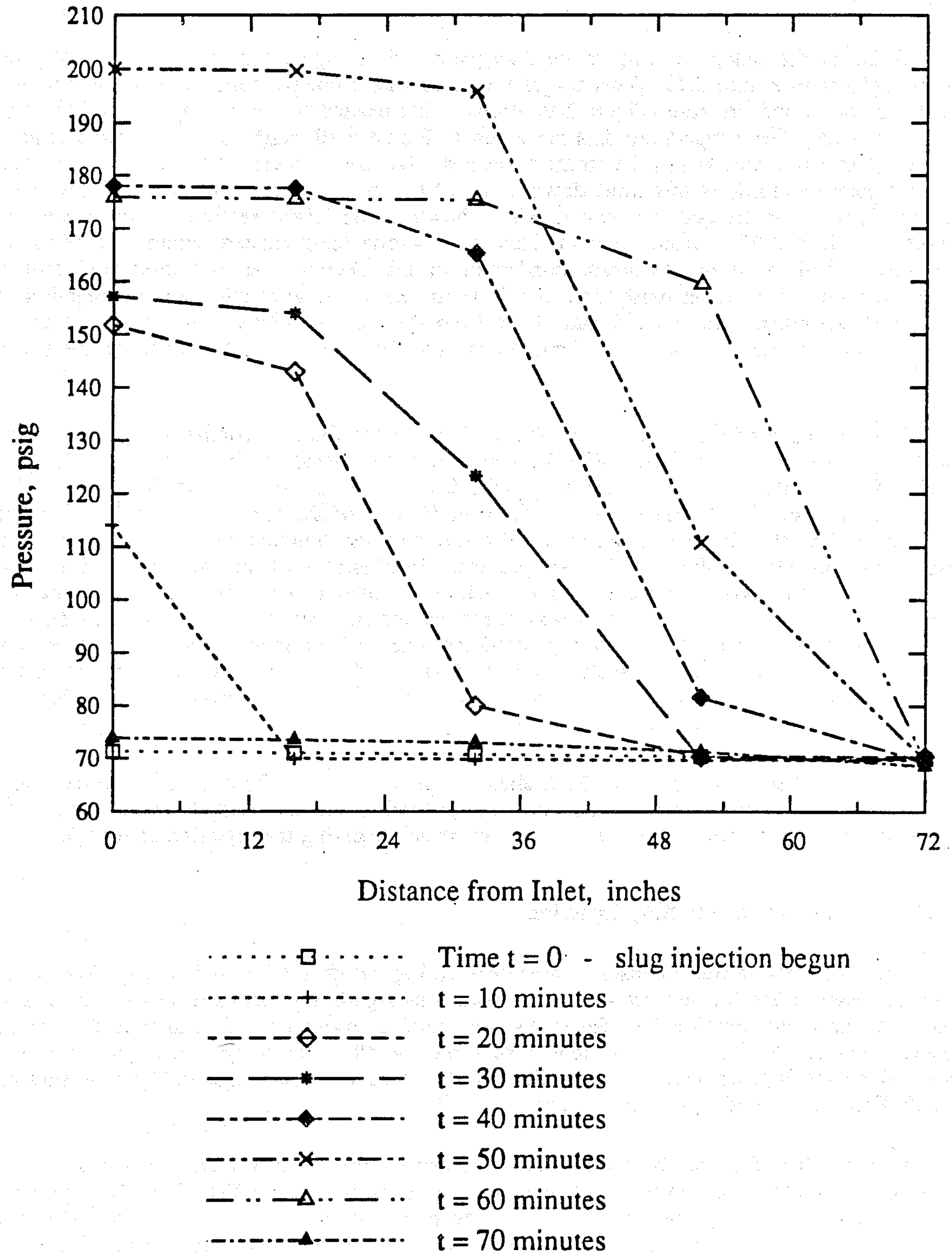

Figure 5.9 : Sandpack Pressure Profiles at Different Times Following Injection of Surfactant Slug in Presence of Nitrogen

the injection of a second slug of the same surfactant concentration resulted in the generation of a stronger foam (J).

Some of the sandpack temperature data presented in Figure 5.8 is shown in a slightly different form in Figure 5.10. This diagram permits direct comparisons to be made between the temperature and pressure (Figure 5.9) profiles that existed following injection of the first surfactant slug. The temperature data presented in Figure 5.10 suggests that 60 minutes after surfactant injection was begun the steam foam had advanced at most 40 inches into the pack. The temperature profile at this time, downstream of this point suggests that most of the steam had condensed, yet the high pressure gradient shown in the fourth section (between pressure tappings 52 in and 72 in from the inlet) indicates a strong foam existed within that section at that time. With most of the steam condensed in this section, the high pressure gradient observed within this region must have largely been due to the generation and propagation of nitrogen foam rather than steam foam. Thus from these observations it would appear that a nitrogen foam formed and advanced through the one-dimensional model ahead of the steam foam.

The existence of a nitrogen foam ahead of the steam foam is confirmed by the experimental observations made during Run 25 which was conducted in the absence of nitrogen. During Run 25, the injection of two slugs of a 0.10 wt % solution of Shell's Enordet AOS 2024 was followed by the injection of a 0.25 wt % slug of the same surfactant†. All slugs were injected in the absence of nitrogen. The pressure and temperature profiles observed in response to injection of the first slug are presented in Figures 5.11 and 5.12 respectively. A comparison of the two diagrams shows a much better match in the position of the leading edges of the fronts at all times, than was observed during a similar run when nitrogen was injected. As an example, 40 mintues after commencement of surfactant injection, the sandpack thermocouples indicated the temperature front had advanced 49 inches into the pack, while the pressures recorded suggested that the pressure front was close to the pressure tapping located 52 inches from the sandpack inlet.

The movement of the pressure front ahead of the temperature front is not observed when the non-condensible nitrogen gas is not present, confirming the existence of a non-condensible gas foam ahead of the steam foam in those experiments involving the injection of nitrogen.

5.2.2. Heat Losses During Slug Injection

The variations in the sandpack temperature during the generation and propagation of the foam discussed in the last section were accompanied by significant variations in the rate of heat lost from the one-dimensional model to the surrounding insulation. To illustrate this point, consider Figures 5.13 and 5.14 which present the variations in temperature and heat flux recorded by the top, upstream sensor following the injection of a single 0.10 wt % slug of Shell's Enordet AOS 1618 surfactant during Run 30.

Prior to slug injection the temperature recorded by the sensor's thermocouple was constant, just below the steam saturation temperature at 70 psig (Figure 5.13). Initially, following the beginning of slug injection the sandpack began to cool as the partial pressure of steam within the pack at that distance from the inlet began to decrease. About 30 minutes following commencement of injection, the steam front passed the sensor's location and the sandpack

† This run is discussed in more detail in Section 5.4 of this report.

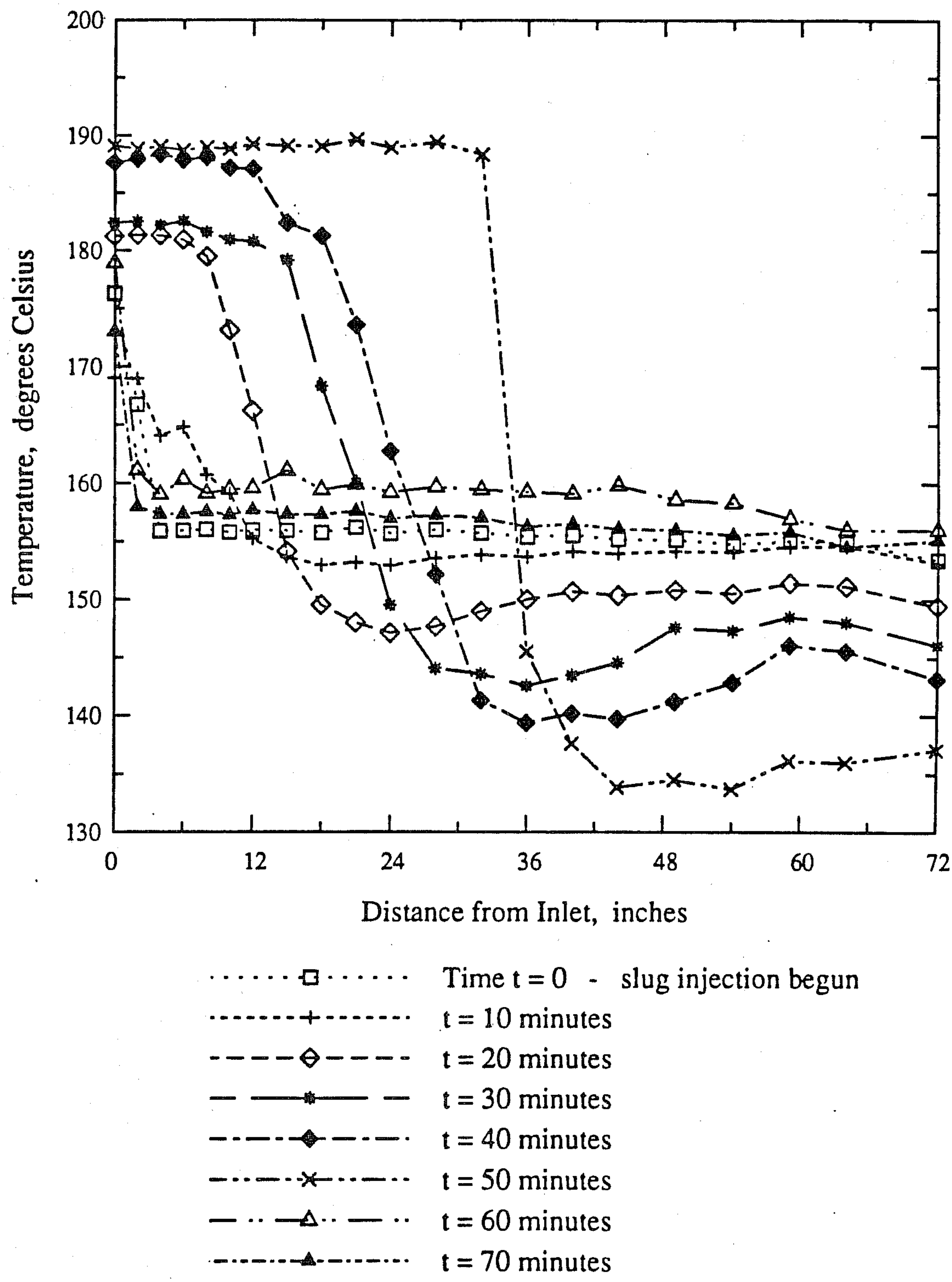

Figure 5.10 : Sandpack Temperature Profiles at Different Times Following Injection of Surfactant Slug in Presence of Nitrogen

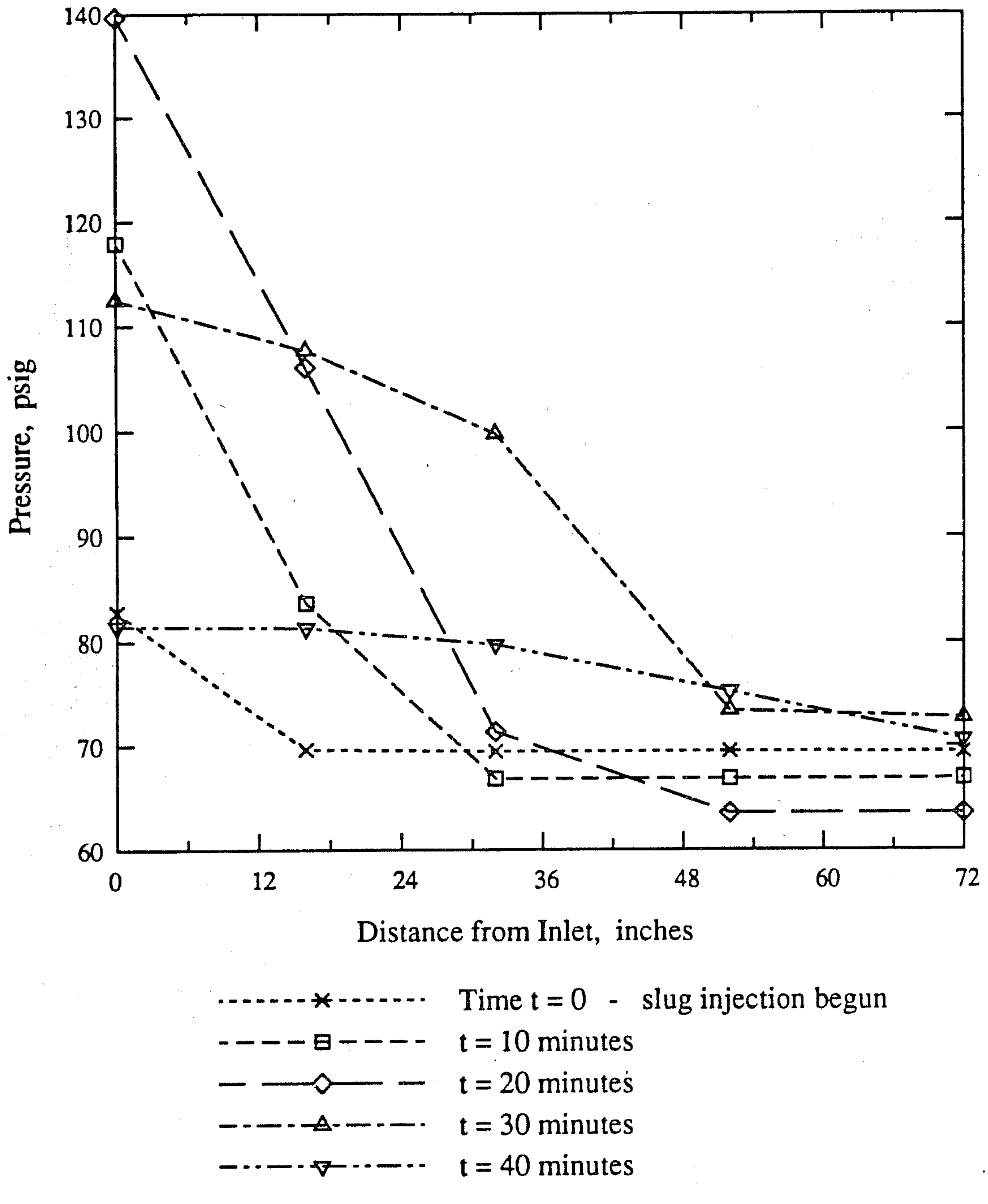

Figure 5.11 : Sandpack Pressure Profiles at Different Times Following Injection of Surfactant Slug in Absence of Nitrogen

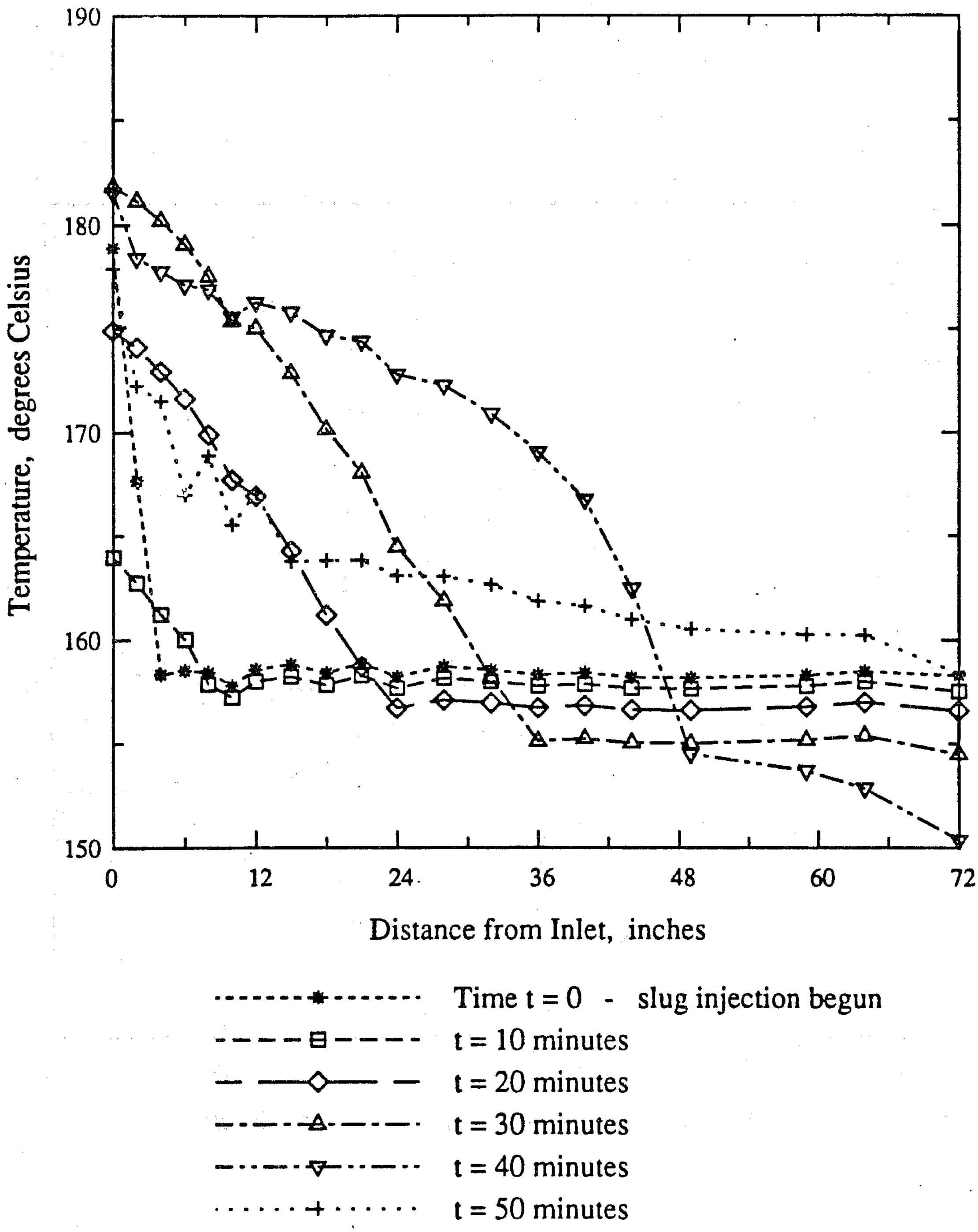

Figure 5.12 : Sandpack Temperature Profiles at Different Times Following Injection of Surfactant Slug in Absence of Nitrogen

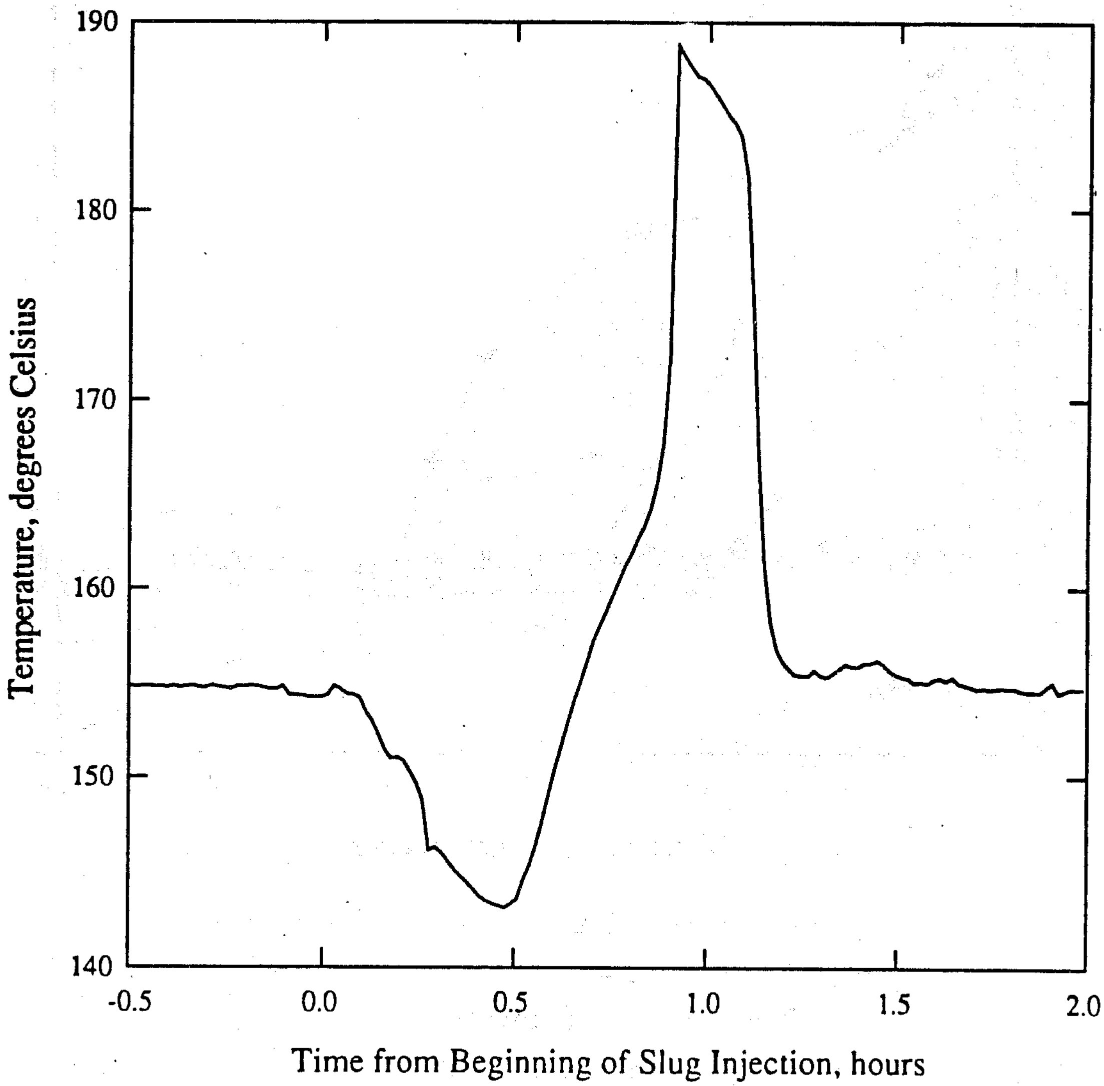

Figure 5.13 : Heat Flux at Exterior Sandpack Wall Measured Using the Top, Upstream Sensor during 70 psig Steamflood

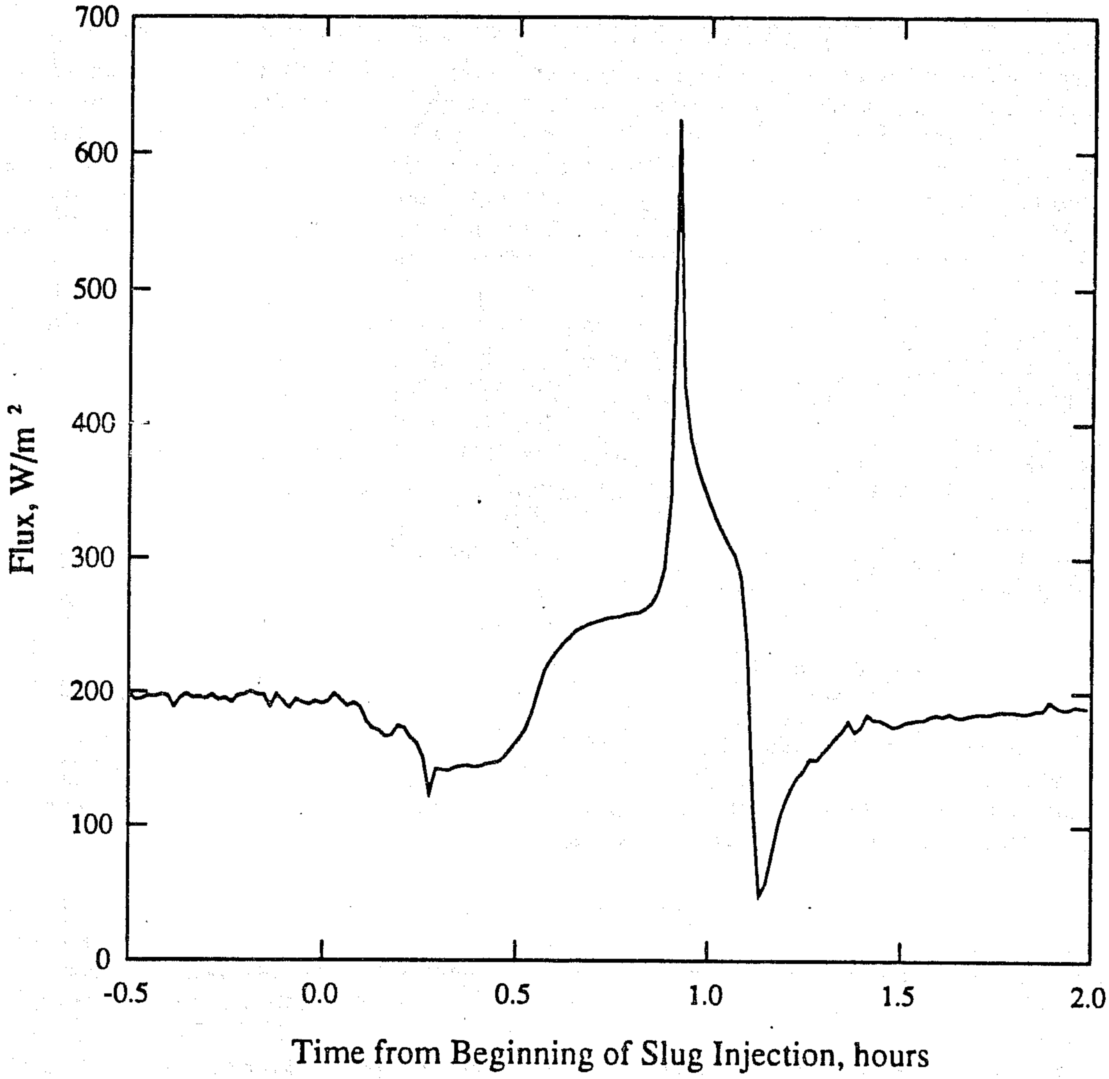

Figure 5.14 : Heat Flux Measured by Top, Upstream Sensor Following Injection of Surfactant Slug

temperature began to increase to 189°C. Then, about 63 minutes following surfactant injection the foam collapsed and the temperature observed by the sensor returned to its pre-injection value.

The variation in the temperature measured by the sensor is inexorably linked to variations in the measured heat flux. Prior to slug injection, the heat flux passing through the top, upstream sensor was constant at 190 W/m^2 (Figure 5.14). Then, as the temperature difference between the sandpack and the insulation began to decrease so too did the rate of heat loss to the insulation. A minimum flux of 143 W/m^2 was observed before the heat flux began to increase as the steam foam approached the sensor's location. A maximum flux of 625 W/m^2 was recorded as the foam front passed the sensor. Shortly thereafter the foam collapsed and the flux dropped to just 48 W/m^2. This is to be expected as during the period of increased heat transfer to the surroundings between 55 and 63 minutes, the temperature of the insulation surrounding the model increased. Thus, when the temperature of the sandpack and the tube returned to their pre-injection levels, the insulation temperature remained slightly elevated. As the insulation cooled, the temperature difference between the tube and the insulation increased resulting in an increase in the heat flux back to the pre-injection level of 190 W/m^2.

Figure 5.14 shows the variation in heat flux recorded at just one location along the tube. During the generation and propagation of the foam within a one-dimensional model, the rate of heat lost to the surroundings is a function not only of time, but of location along the sandpack as well. Figure 5.14 compares the variation in heat fluxes recorded by the two top sensors located 25912 and 38 inches from the sandpack inlet. The difference in the rate of heat losses from the two sensors is obvious. The heat flux recorded by the downstream sensor peaked at a higher value than the upstream sensor (c.f. 819 W/m^2 to 625 W/m^2). This is to be expected because the temperature of the sandpack at the downstream location had longer time to drop to a lower temperature before the arrival of the foam front.

5.3. PRESSURE RESPONSE DATA

One of the main objectives of the experimental programme is to study the foam-forming ability of seventeen surfactants using the one-dimensional model. If the injection of a slug of a surfactant solution results in the spontaneous generation of foam within the pack, this will be indicated by an increase in the injection pressure.

In the following section the pressure responses to the injection of the different surfactants are presented and discussed, surfactant by surfactant. During the experiments the total pressure drop across the tube was recorded and is presented diagrammatically for each surfactant that induced foaming. The variations in the pressure gradients in each of the four sections are also presented. In these diagrams the 'first section' refers to the 16 inch (40.6 cm) upstream section; the 'second section' refers to the 16 inch section between the pressure tappings located 16 inches and 32 inches (81.3 cm) from the tube inlet; the 'third section' refers to the 20 inch (50.8 cm) section between the pressure tappings 32 inches and 52 inches (132.1 cm) from the tube inlet; and the 'fourth section' refers to the 20 inch section between the pressure tapping located 52 inches from the inlet, and the tube outlet.

The main pressure response data for each of the surfactants is summarized in a series of tables presented at the end of this chapter. An effort was made to assess the duration of the pressure response observed in each of the tube sections. The duration of the pressure response is defined as the time between when the pressure drop begins to increase at a rate greater than 1 psi/min, and when the pressure drop begins to decrease at a rate less than 1 psi/min.

5.3.1. No Added Surfactant (Control Run)

Before commencing the series of experiments injecting slugs of different surfactants, a run was performed in which two 10 percent pore volume slugs of water were injected. No increase in the pressure distribution within the system was detected in response to the injection of the two slugs. Any increase observed in later experiments must therefore be due exclusively to the generation of foam within the sandpack.

5.3.2. Chevron Chaser SD 1000 (Run 6)

Four slugs of a 0.1 percent by active weight solution of Chevron's Chaser SD 1000 were injected into the one-dimensional sandpack during Run 6. Figure 5.15 shows the variation with time of the measured pressure drop across the length of the tube. Significant increases in the pressure drop (ΔP) are observed in response to the injection of each of the slugs. These responses suggests that foam generated spontaneously within the sandpack. Three main points may be noted from the diagram. Firstly, the magnitude of the pressure response increases with succeeding slugs. The first slug produces an increase of 6.4 psi across the tube, while later slugs result in pressure drops of 23.1, 52.2 and finally 72.3 psi (Table 5.1). This observation suggests that between injection of the slugs some surfactant remains within the sandpack. Secondly, after each response has died down, the observed pressure drop does not return to its pre-injection value, but instead, to a slightly higher value (e.g. compare ΔP at t=5 hr with ΔP at t=13 hr). Finally, the foam appears to collapse substantially immediately after injection of the surfactant is stopped.

Figure 5.16 shows the variations with time in the pressure gradients observed for the four tube sections. This diagram indicates that foaming commences in the upstream section of the sandpack. It is not until late in the injection of the third slug that foaming is observed in the second sandpack section, as indicated by an increase in the pressure gradient in that section. At this time, the pressure gradient in the first section stabilizes. During injection of the final slug, the pressure gradient in the first section is little greater than it was in response to injection of the third slug. The increased pressure drop across the tube that was observed is caused by the advancement of the foam front into the second section of the tube.

The variation in the system back pressure during Run 6 is shown in Figure 5.17. During the pre-surfactant steamflood (0.5 hr $< t <$ 4.3 hr) the back pressure was held constant at 70 psig with little variation. The slight increase in back pressure observed at t = 4.3 hr corresponds to the commencement of nitrogen injection. The sharp increase in the back pressure at t = 11.1 hr was caused by a problem with the back pressure regulator that was rectified without stopping the experiment.

The main pressure response data observed during Run 6 is summarized in Table 5.1 at the end of this chapter.

5.3.3. Chevron Chaser SD 1020 (Runs 15 and 34)

Experiments were performed using two different samples of Chevron's Chaser SD 1020 provided by the manufacturer. In neither run was foaming observed. Solutions of 0.10 wt %, 0.25 wt % and 0.50 wt % of the surfactant were injected during Run 15. Figure 5.18 shows that the pressure drop across the sandpack did not respond significantly to the injection of any of the three slugs. (Note the expanded pressure scale in the diagram.) A 1.0 wt % solution

Table 5.1 : Summary of Pressure Response Data for Chevron Chaser SD 1000 (Run 6)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	0.10	0.10
Slug Injection					
Start Time (hr)		5.883	7.891	10.369	12.180
Stop Time (hr)		6.510	8.481	11.083	12.770
Duration (min)		37.6	35.4	42.8	35.4
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	6.4	22.6	45.4	48.5
	Time (hr)	6.46	8.45	10.91	12.62
Section 2	ΔP_2 (psi)	--	--	7.5	28.8
	Time (hr)	--	--	11.11	12.74
Section 3	ΔP_3 (psi)	--	--	--	--
	Time (hr)	--	--	--	--
Section 4	ΔP_4 (psi)	--	--	--	--
	Time (hr)	--	--	--	--
Entire Tube	ΔP (psi)	6.4	23.1	52.2	72.3
	Time (hr)	6.46	8.47	11.06	12.74
Duration of Pressure Response†					
Section 1	Time (min)	29	> 34 **	41	32
Section 2	Time (min)	--	--	13	27
Section 3	Time (min)	--	--	--	--
Section 4	Time (min)	--	--	--	--
Entire Tube	Time (min)	29	> 34 **	41	32
Response Time Lag (min)		22	5	5	8

† Duration of pressure response as defined in Section 5.2.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

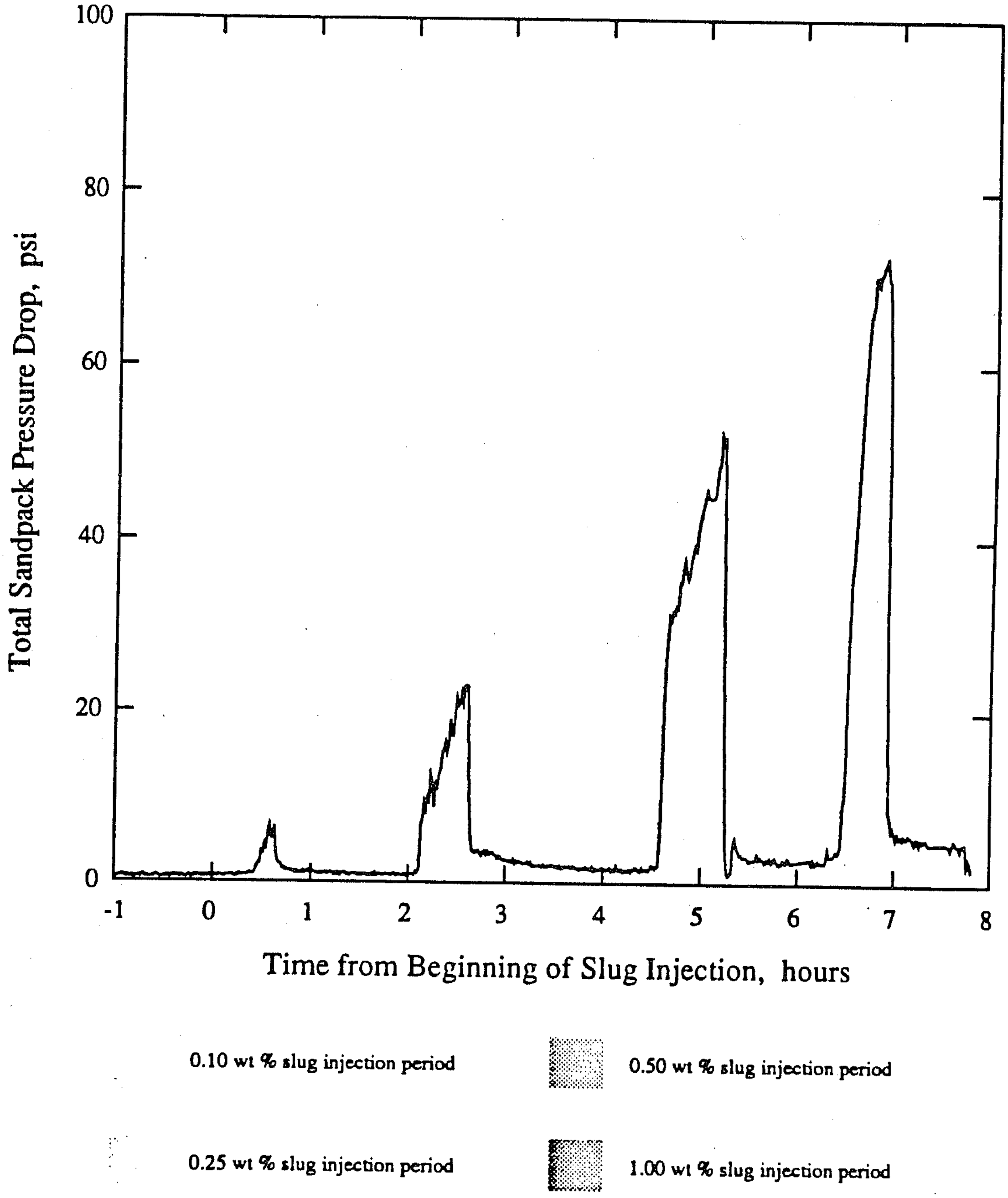

Figure 5.15 : Total Pressure Drop Response to Injection of Four Slugs of Chevron Chaser SD 1000 - Run 6

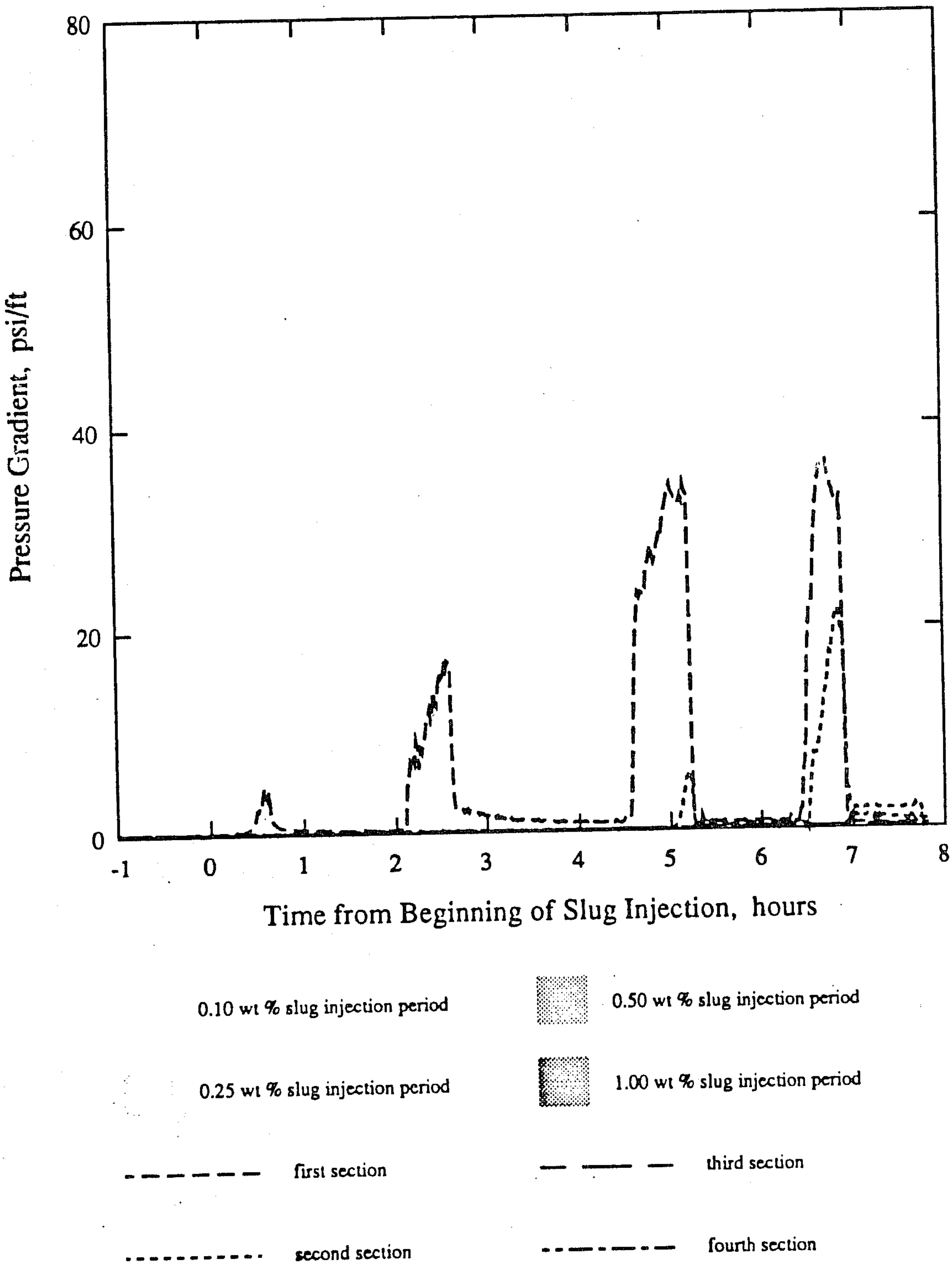

Figure 5.16 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Four Slugs of Chevron Chaser SD 1000 - Run 6

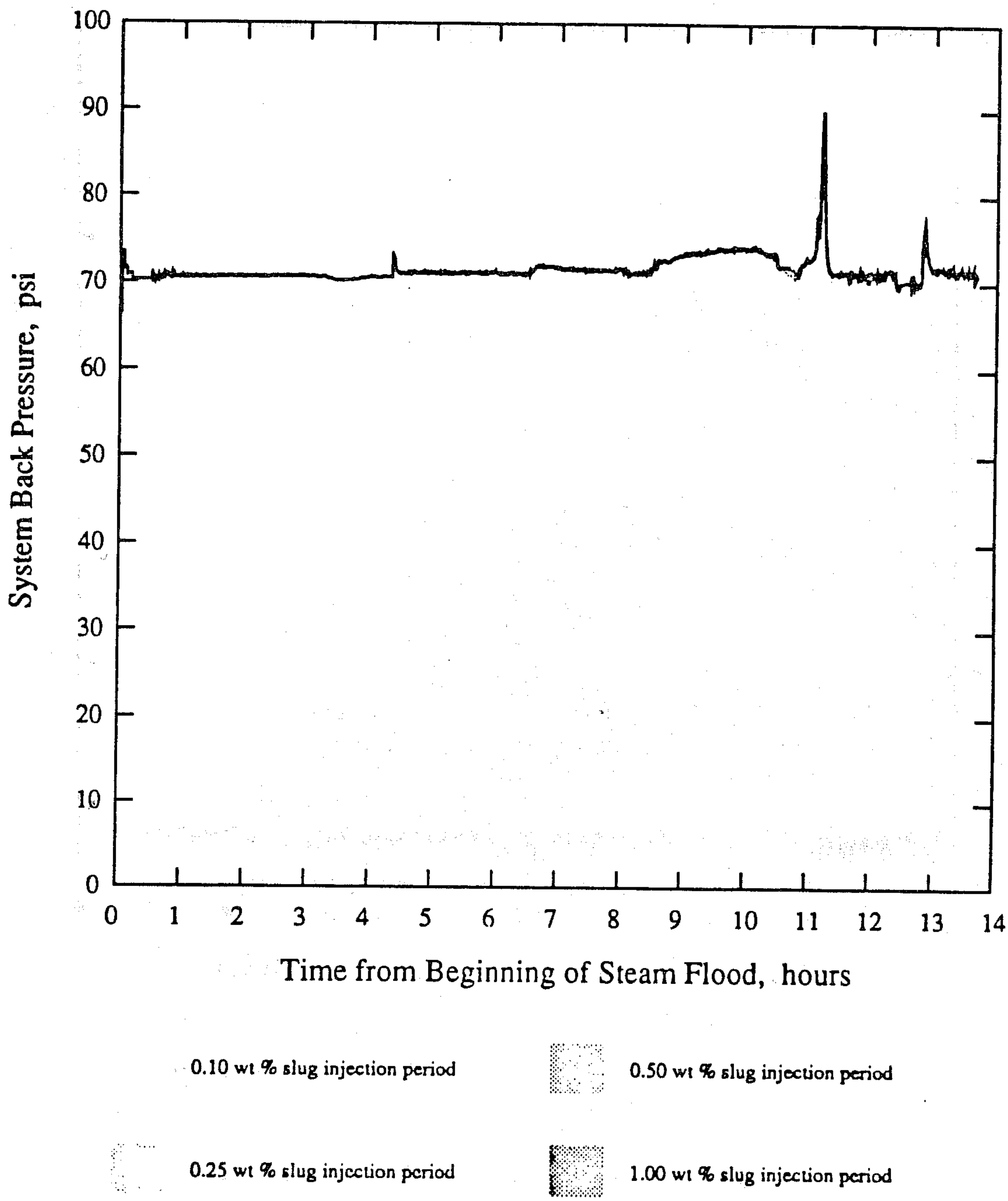

Figure 5.17 : System Back Pressure during Run 06

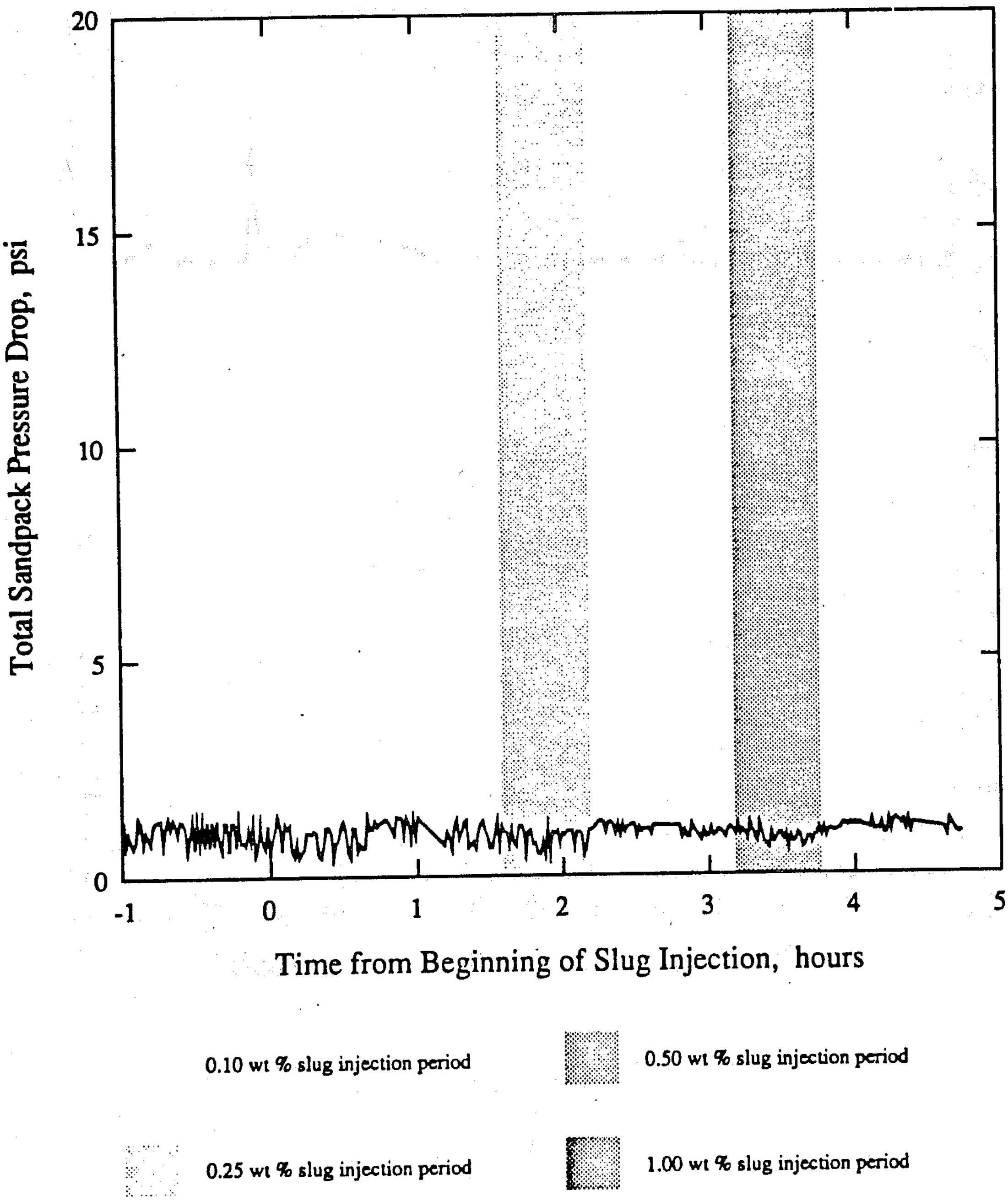

Figure 5.18 : Total Pressure Drop Response to Injection of Three Slugs of Chevron Chaser SD 1020 - Run 15

was prepared but it was found that it could not be injected by the surfactant injection pump due to its high viscosity.

A second sample of the surfactant was received from Chevron. There was a noticeable difference in colour between the two samples and it was found that the surfactant injection pump could inject a slug of 1.0 wt % concentration of this second sample. However, even at this high concentration no foaming was observed in the sandpack during Run 34.

At the conclusion of both runs, when the pressure within the tube was being released at the outlet end, foam was produced from the sandpack. It is believed however that this foam was produced solely due to the pressure difference imposed on the downstream end of the tube by the sudden depressurization at the outlet. Thus, this foam was induced rather than being spontaneously generated within the sandpack.

5.3.4. Hoechst Hostapur OS fl (Run 18)

The ability of Hoechst's Hostapur OS fl surfactant to foam foam was studied during Run 18. The injection of a single 0.10 wt % slug was followed by the injection of three slugs of a 0.25 wt % solution. The variation in the total pressure drop across the system is shown in Figure 5.19. The data clearly shows that no foam was generated by the injection of the first, 0.10 wt % slug. The surfactant did foam however in response to the injection of the three more concentrated slugs. Not only did the magnitude of the maximum pressure drop observed increase with the injection of succeeding slugs, but so too did the duration of the response (also see Table 5.2). The maximum observed pressure drop increased from 65.1 psi for the second slug, to 80.0 psi for the third slug, and finally to 148.3 psi in response to the last slug. The pressure response duration of 45 minutes for the second slug was nearly doubled by the 82 minute duration of the fourth slug response.

Figure 5.20 shows the variation in the pressure gradients across each of the four tube sections. This diagram shows that during the injection of the second slug, foam was observed in the first three tube sections. As soon as the injection of this slug stopped, the foam immediately collapsed. In response to the injection of the next two slugs foam was generated in the fourth tube section. Foam formation in the fourth section continued after the injection of the surfactant had stopped. Also, it was the foam generated in this downstream section which was responsible for the significant increase in the pressure drop observed in response to the injection of the fourth slug.

The variation in the system back pressure during Run 18 is presented in Figure 5.21. The significant deviations from 70 psig at t = 12.4 hr were brought about by the production of foam at the outlet. This necessitated the back pressure be controlled manually rather than by the regulator. Once foam production ceased, the regulator resumed control.

5.3.5. Hoechst Hostapur SAS 60 (Run 19)

The second Hoechst surfactant was studied in Run 19. Slugs of 0.10 wt %, 0.25 wt % and 0.50 wt % of Hostapur SAS 60 surfactant were injected into the sandpack. A plot of total pressure drop across the tube with time (Figure 5.22) clearly shows that foaming did not occur in response to the injection of the two more dilute slugs. Foaming occurred almost immediately after the injection of the 0.50 wt % slug began, with a maximum pressure drop of greater than 214 psi being observed. Foaming was observed in all four sections as shown in Figure 5.23. Foaming was so strong in the fourth section that the 100 psi pressure transducer

Table 5.2 : Summary of Pressure Response Data for Hoechst Hostapur OS fl (Run 18)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	0.25	0.25
Slug Injection					
Start Time (hr)		5.118	6.731	8.800	11.092
Stop Time (hr)		5.708	7.322	9.391	11.682
Duration (min)		35.4	35.4	35.4	35.4
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	38.8	44.0	39.5
	Time (hr)	--	6.92	8.91	11.20
Section 2	ΔP_2 (psi)	--	38.5	45.3	51.4
	Time (hr)	--	7.11	9.08	11.30
Section 3	ΔP_3 (psi)	--	29.6	63.0	68.4
	Time (hr)	--	7.35	9.26	11.53
Section 4	ΔP_4 (psi)	--	--	45.9	117.4
	Time (hr)	--	--	9.45	12.16
Entire Tube	ΔP (psi)	--	65.1	80.0	148.3
	Time (hr)	--	7.31	9.22	12.16
Duration of Pressure Response†					
Section 1	Time (min)	--	40	20 **	36
Section 2	Time (min)	--	34 **	25 **	38
Section 3	Time (min)	--	16	41 **	72
Section 4	Time (min)	--	--	25	59
Entire Tube	Time (min)	--	45 **	52 **	82 **
Response Time Lag (min)		--	2	3	3

† Duration of pressure response as defined in Section 5.2.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

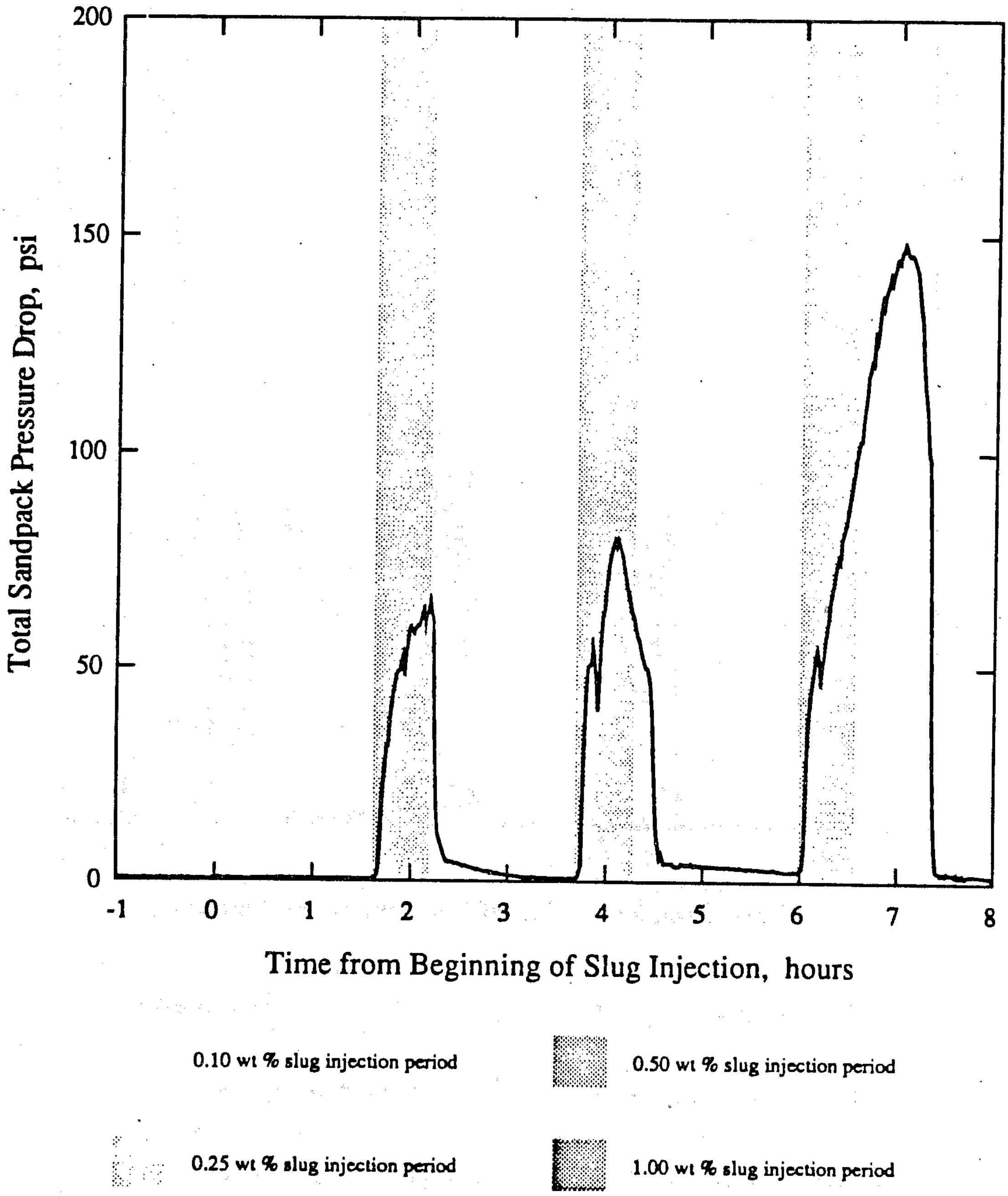

Figure 5.19 : Total Pressure Drop Response to Injection of Four Slugs of Hoechst Hostapur OS fl - Run 18

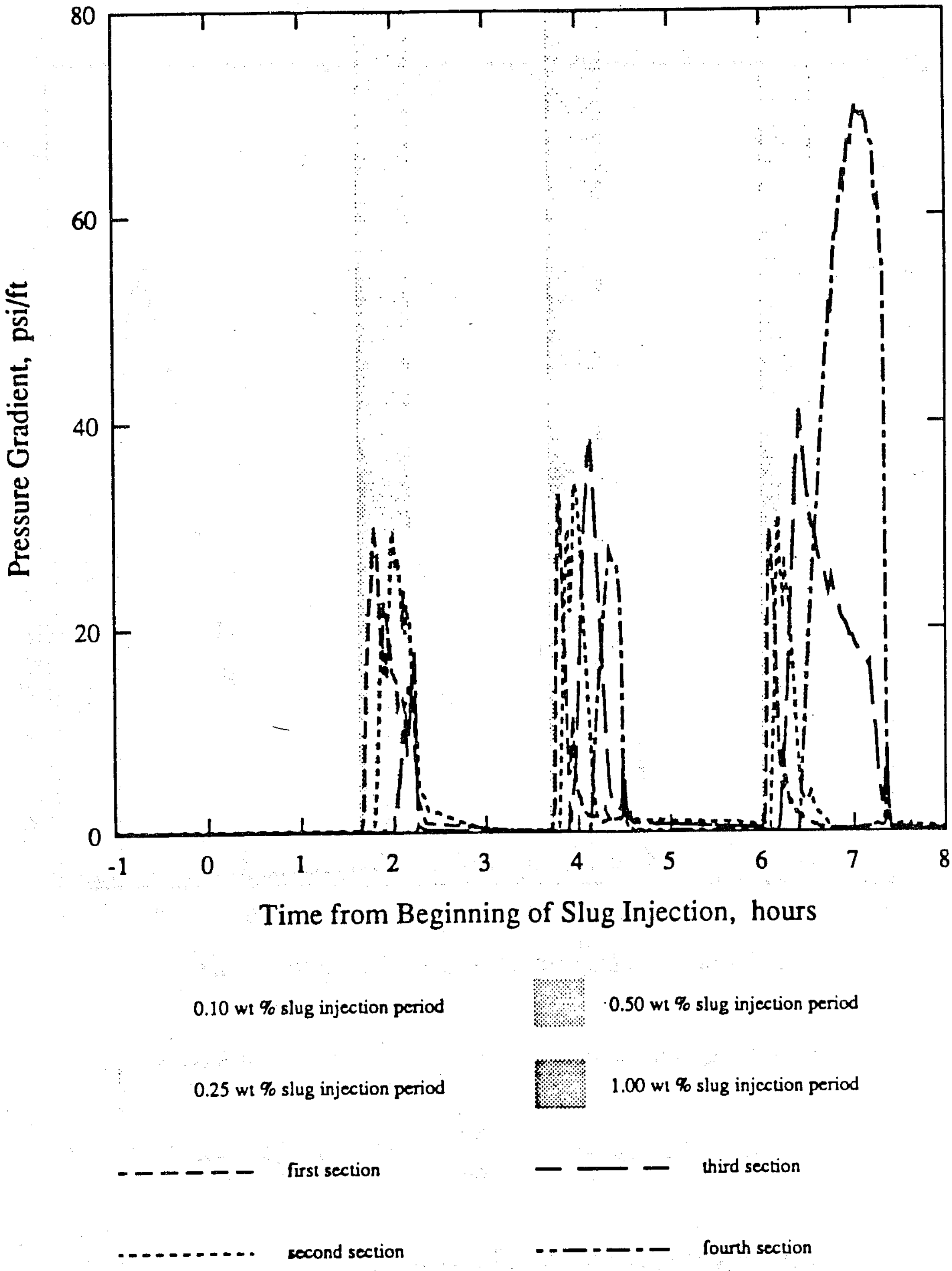

Figure 5.20 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Four Slugs of Hoechst Hostapur OS fl - Run 18

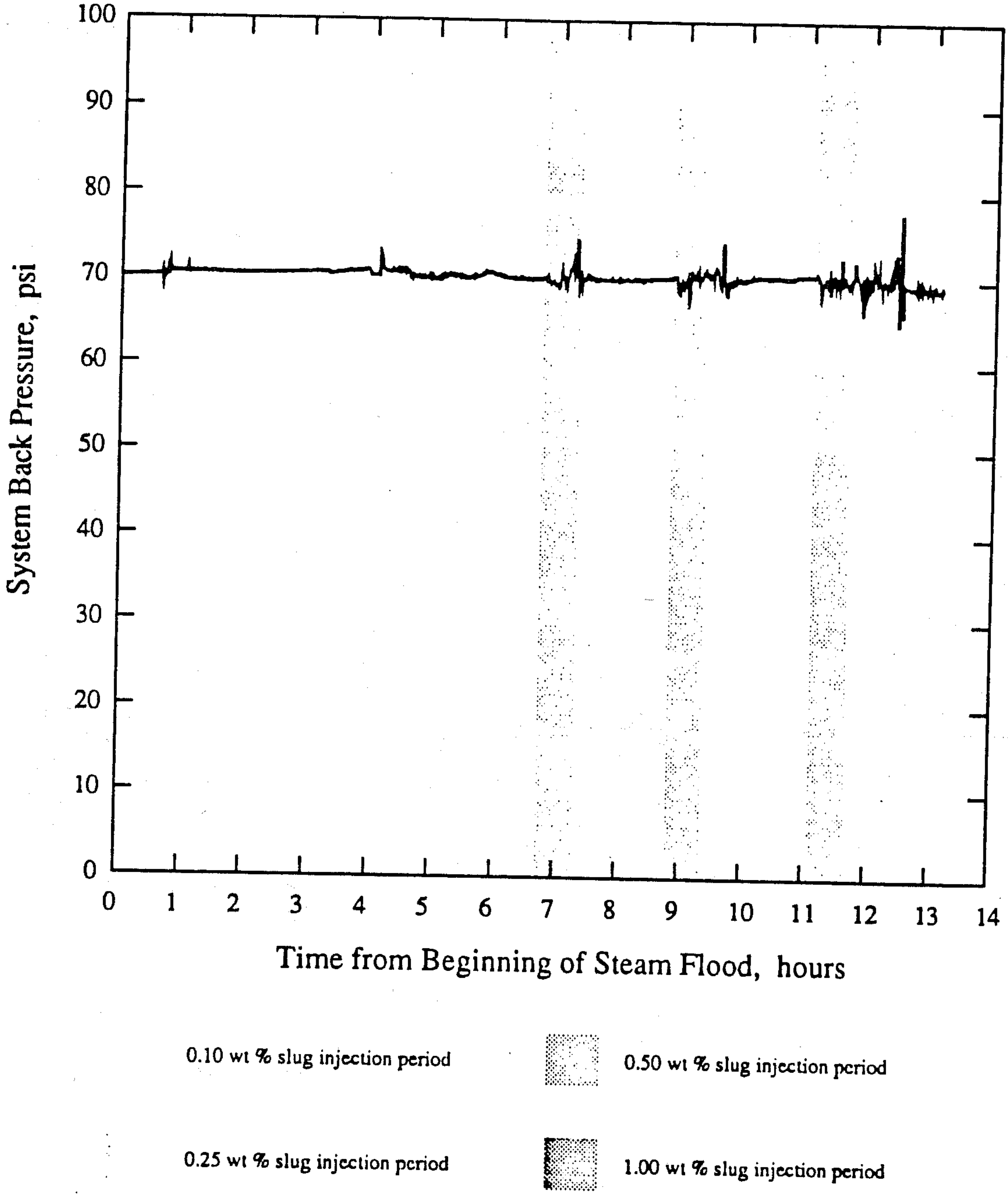

Figure 5.21 : System Back Pressure during Run 18

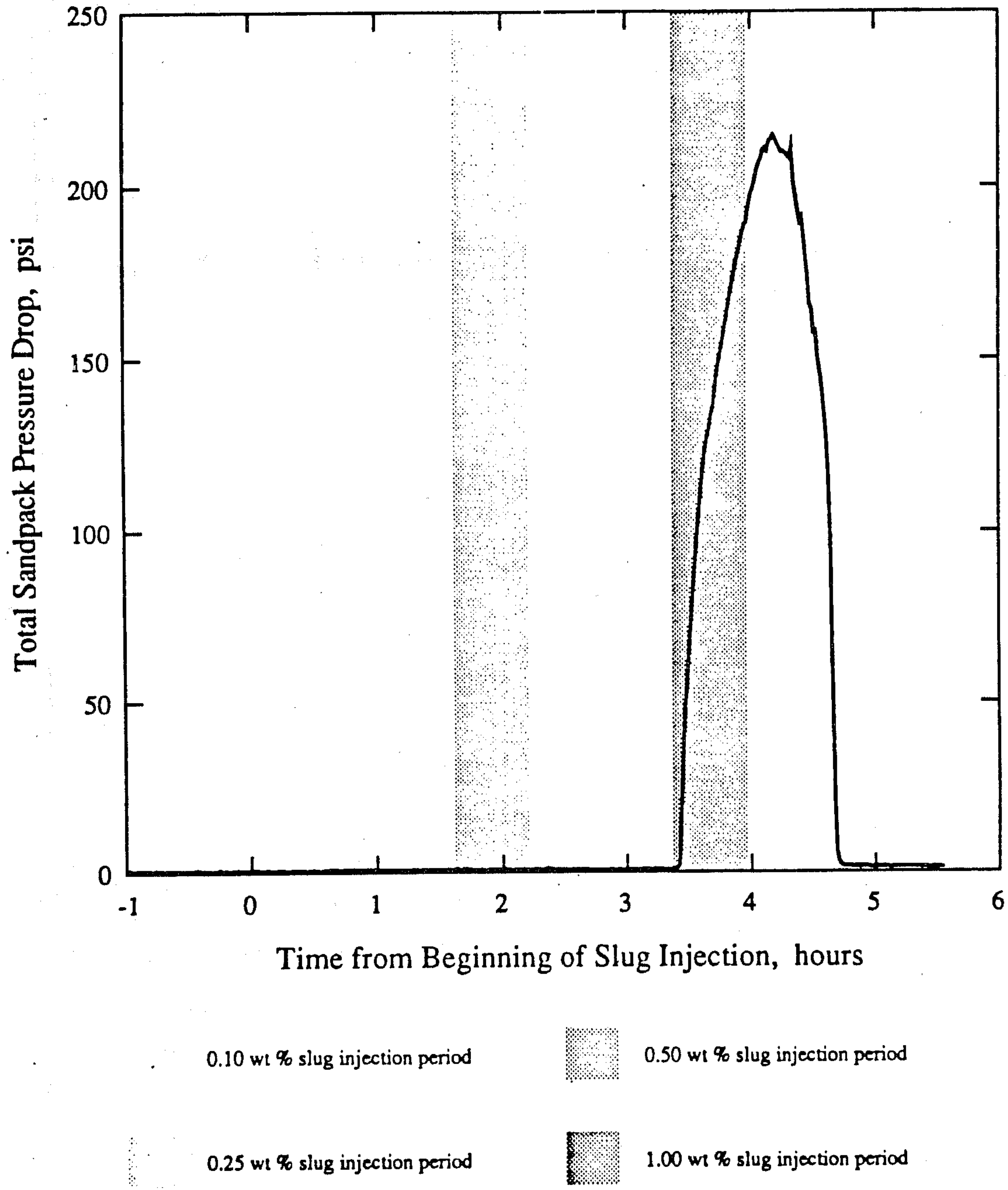

Figure 5.22 : Total Pressure Drop Response to Injection of Three Slugs of Hoechst Hostapur SAS60 - Run 19

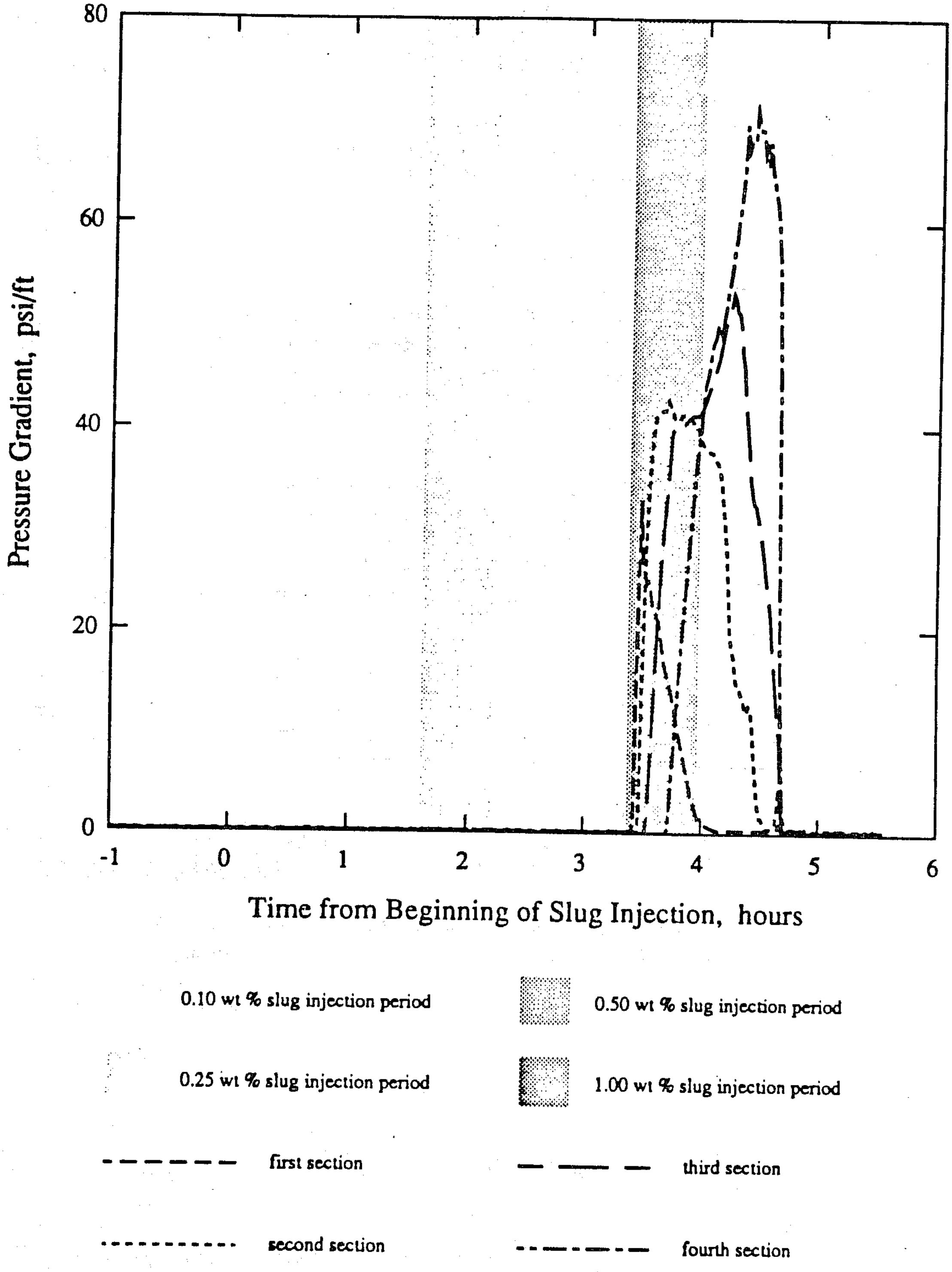

Figure 5.23 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Hoechst Hostapur SAS60 - Run 19

recording the pressure drop across this section overranged. The maximum recorded pressure in this section was 118 psi, but the actual pressure drop was probably higher. Thus, the region around the maximum in the fourth section trace shown in Figure 5.23 is uncertain. The main pressure response data for this run is summarized in Table 5.3.

The variation in the system back pressure during Run 19 is shown in Figure 5.24. The pressure deviated significantly from 70 psig during the injection of the third slug when it dropped to 64 psig due to the mechanism described in Section 5.2.1.

5.3.6. Shell C1416 AOS (Runs 7 and 8)

Two runs were performed early in the experimental programme using Shell's C1416 AOS, an alpha-olefin sulphonate surfactant whose molecules contained either 14 or 16 carbon atoms in the alkyl chain. During Run 7 three slugs of a 0.1 wt % solution were injected. A plot of total pressure drop across the tube with time clearly shows that no foam was spontaneously generated within the sandpack (Figure 5.25).

This experiment was followed by Run 8 during which three slugs of a 0.5 wt % solution were injected at intervals of over two hours. Figure 5.26 clearly shows that foam was observed in response to the injection of all three slugs. The information presented in Table 5.4 shows that the foam produced was relatively long-lived. In response to the injection of the second slug the foam persisted for 123 minutes, 87 minutes after the surfactant injection had stopped.

The information presented in Figure 5.27 shows that foaming did not occur in the fourth tube section in response to the injection of the first slug. Very strong foam did occur in the two downstream sections in response to the latter two slugs. Indeed, the foam generated within the fourth section in response to the second and third slugs was so strong that the pressure drop imposed by the foam exceeded the measurement limits of the 100 psi transducer. This is the cause for the plateau observed in the fourth section gradient trace in Figure 5.27. The maximum pressure drops listed in Table 5.4 for these two slugs, 192 psi and 245 psi, must have been exceeded during the experiment while the pressure transducers were overranging.

Run 8 was performed before the installation of the manual back pressure control system. As a consequence these was no satisfactory method of adequately controlling the system back pressure while foam was being produced. Figure 5.28 clearly indicates the significant control problems that were encountered while foam was passing through the back pressure regulator.

5.3.7. Shell Enordet AOS 1618 (Runs 10, 30, 31 and 32)

Four experiments were conducted using Shell's Enordet AOS 1618 surfactant, a surfactant successfully used in various oil fileds to generate steam foam. Runs 31 and 32 were performed with the system back pressure set at 100 psig (790 kPa) and 40 psig (380 kPa) respectively, and the results of these runs are discussed in Section 5.5. The experimental conditions of Runs 10 and 30 are virtually identical and may be used to indicate the reproducibility of the experimental technique. In both experiments two slugs of a 0.10 wt % solution of Enordet AOS 1618 were injected.

Figure 5.29 shows the variation with time of the pressure drop across the tube for Run 10. Foam was generated in response to the injection of both slugs with the pressure drop

Table 5.3 : Summary of Pressure Response Data for Hoechst Hostapur SAS 60 (Run 19)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	0.50	--
Slug Injection					
Start Time (hr)		5.054	6.668	8.426	--
Stop Time (hr)		5.647	7.258	9.016	--
Duration (min)		35.6	35.4	35.4	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	--	43.9	--
	Time (hr)	--	--	8.53	--
Section 2	ΔP_2 (psi)	--	--	42.7	--
	Time (hr)	--	--	8.74	--
Section 3	ΔP_3 (psi)	--	--	88.5	--
	Time (hr)	--	--	9.29	--
Section 4	ΔP_4 (psi)	--	--	> 118 ‡	--
	Time (hr)	--	--	9.47 ‡	--
Entire Tube	ΔP (psi)	--	--	> 214.5 ‡	--
	Time (hr)	--	--	9.24 ‡	--
Duration of Pressure Response†					
Section 1	Time (min)	--	--	41	--
Section 2	Time (min)	--	--	75	--
Section 3	Time (min)	--	--	69	--
Section 4	Time (min)	--	--	59	--
Entire Tube	Time (min)	--	--	76	--
Response Time Lag (min)		--	--	3	--

† Duration of pressure response as defined in Section 5.2.

‡ Transducers overranged during slug injection.

Table 5.4 : Summary of Pressure Response Data for Shell C1416 AOS (Run 8)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.50	0.50	0.50	--
Slug Injection					
Start Time (hr)		5.191	8.027	10.576	--
Stop Time (hr)		5.781	8.617	11.167	--
Duration (min)		35.4	35.4	35.4	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	46.3	47.4	46.6	--
	Time (hr)	5.32	8.10	10.66	--
Section 2	ΔP_2 (psi)	53.1	55.5	57.0	--
	Time (hr)	5.52	8.20	10.87	--
Section 3	ΔP_3 (psi)	59.8	85.6	112.3	--
	Time (hr)	5.88	8.45	11.84	--
Section 4	ΔP_4 (psi)	--	> 120 ‡	> 120 ‡	--
	Time (hr)	--	? ‡	? ‡	--
Entire Tube	ΔP (psi)	70.8	> 191.8 ‡	> 245.3 ‡	--
	Time (hr)	5.60	9.54	11.84	--
Duration of Pressure Response†					
Section 1	Time (min)	> 25 **	18	25	--
Section 2	Time (min)	> 31 **	31	> 73 **	--
Section 3	Time (min)	> 78 **	114	94	--
Section 4	Time (min)	--	99	81	--
Entire Tube	Time (min)	118 **	123	103	--
Response Time Lag (min)		2	2	2	--

† Duration of pressure response as defined in Section 5.2.

‡ Transducers overranged during slug injection.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

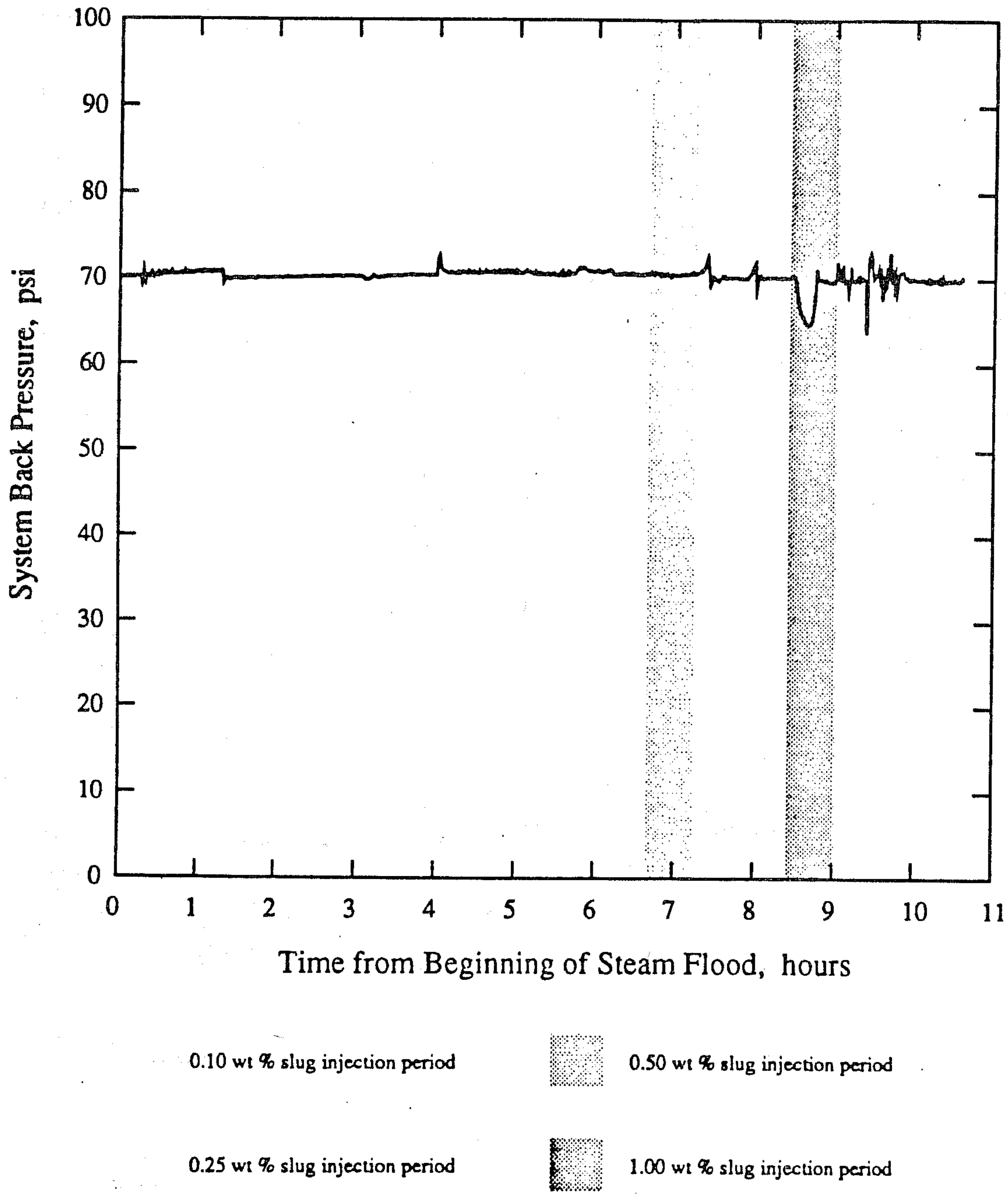

Figure 5.24 : System Back Pressure During Run 19

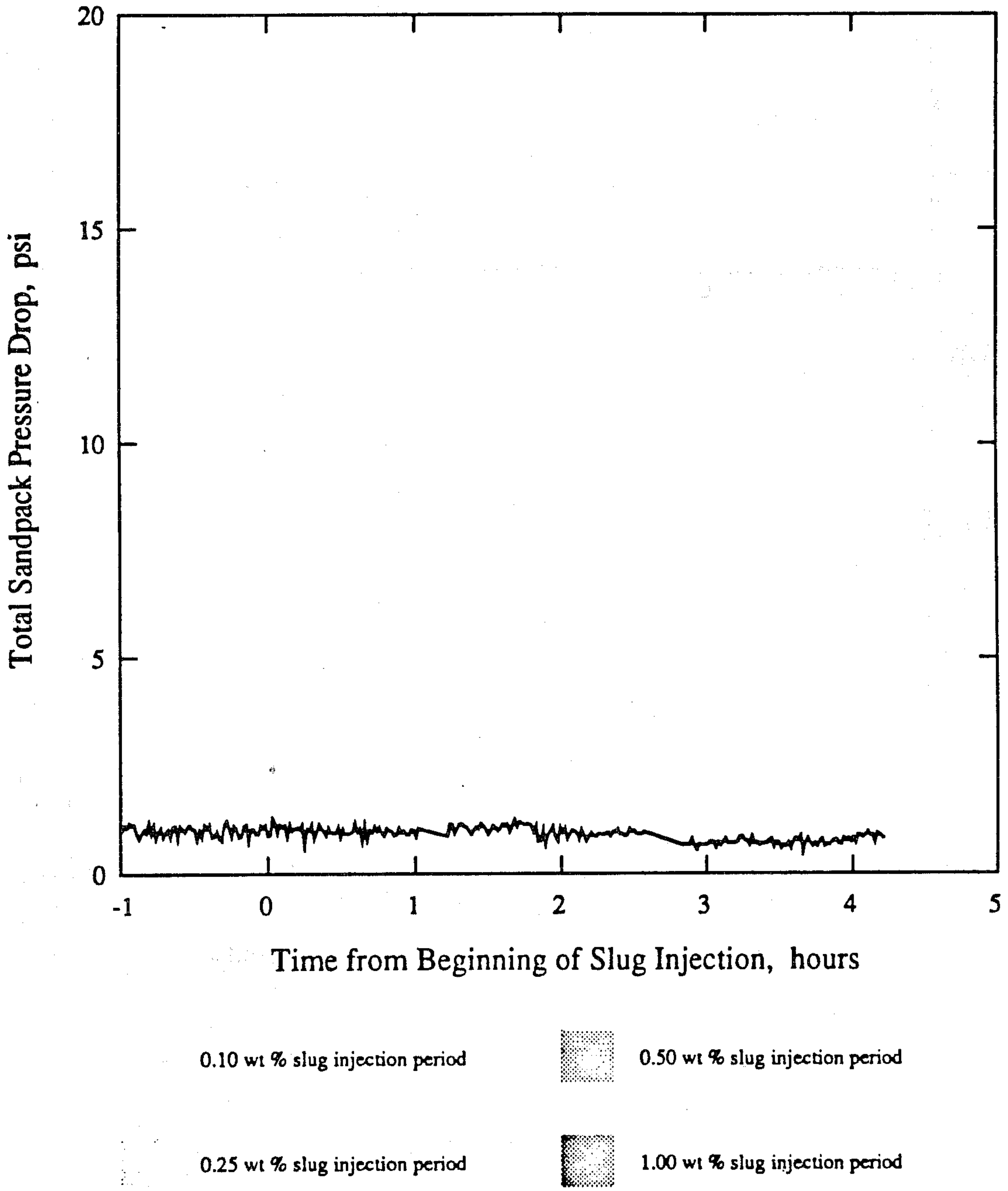

Figure 5.25 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet C1416 AOS - Run 07

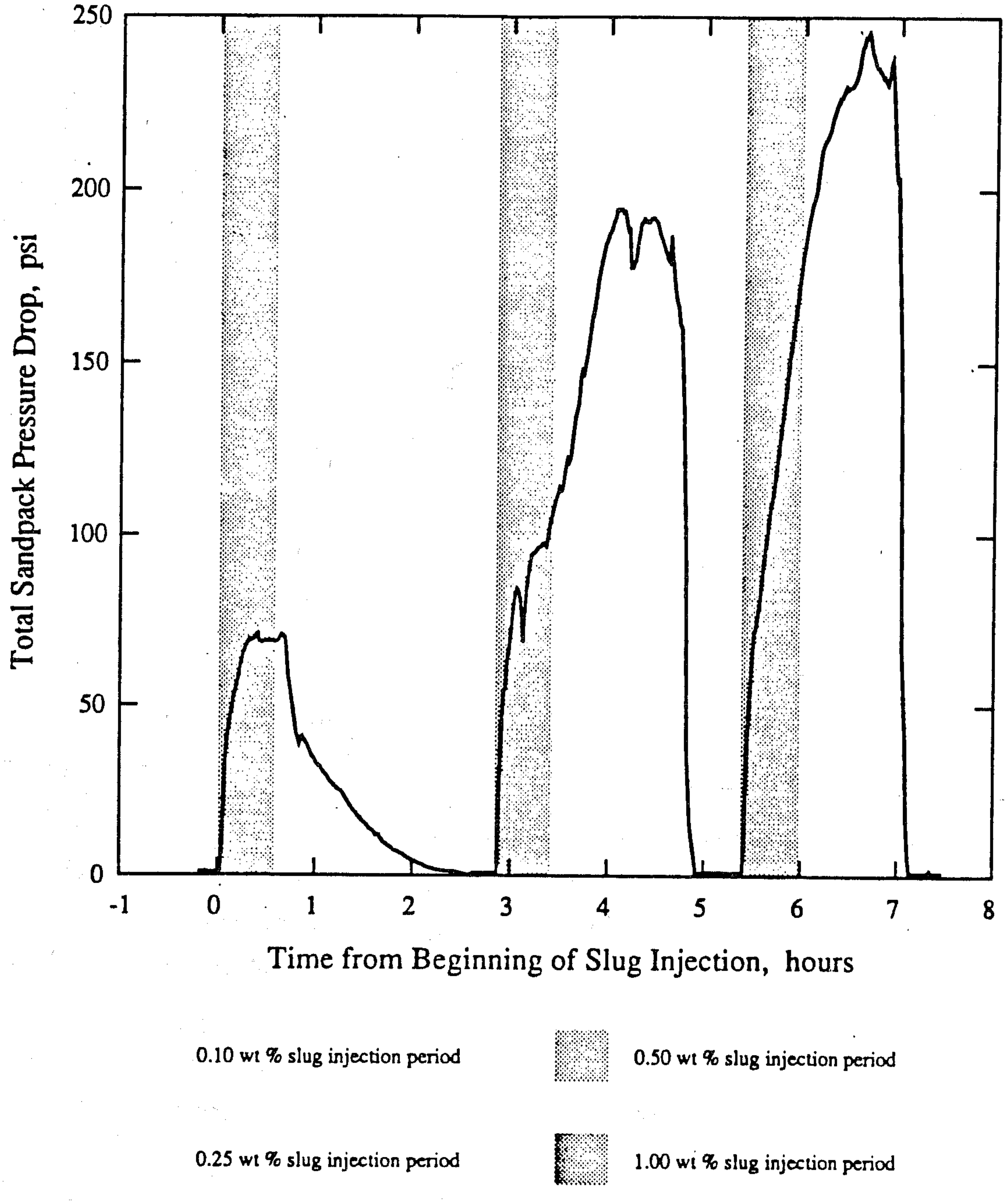

Figure 5.26 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet C1416 AOS - Run 08

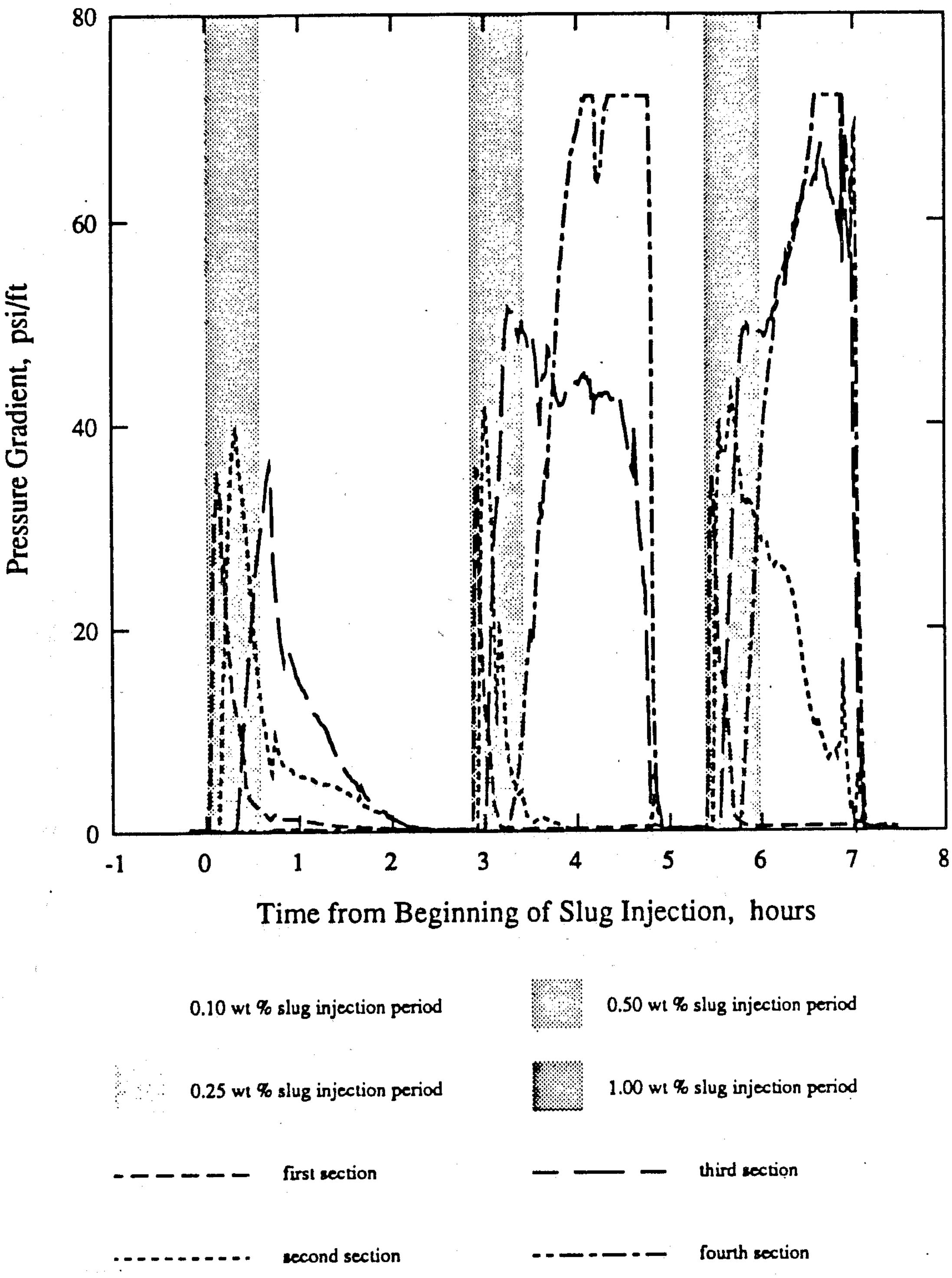

Figure 5.27 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Shell C1416 AOS

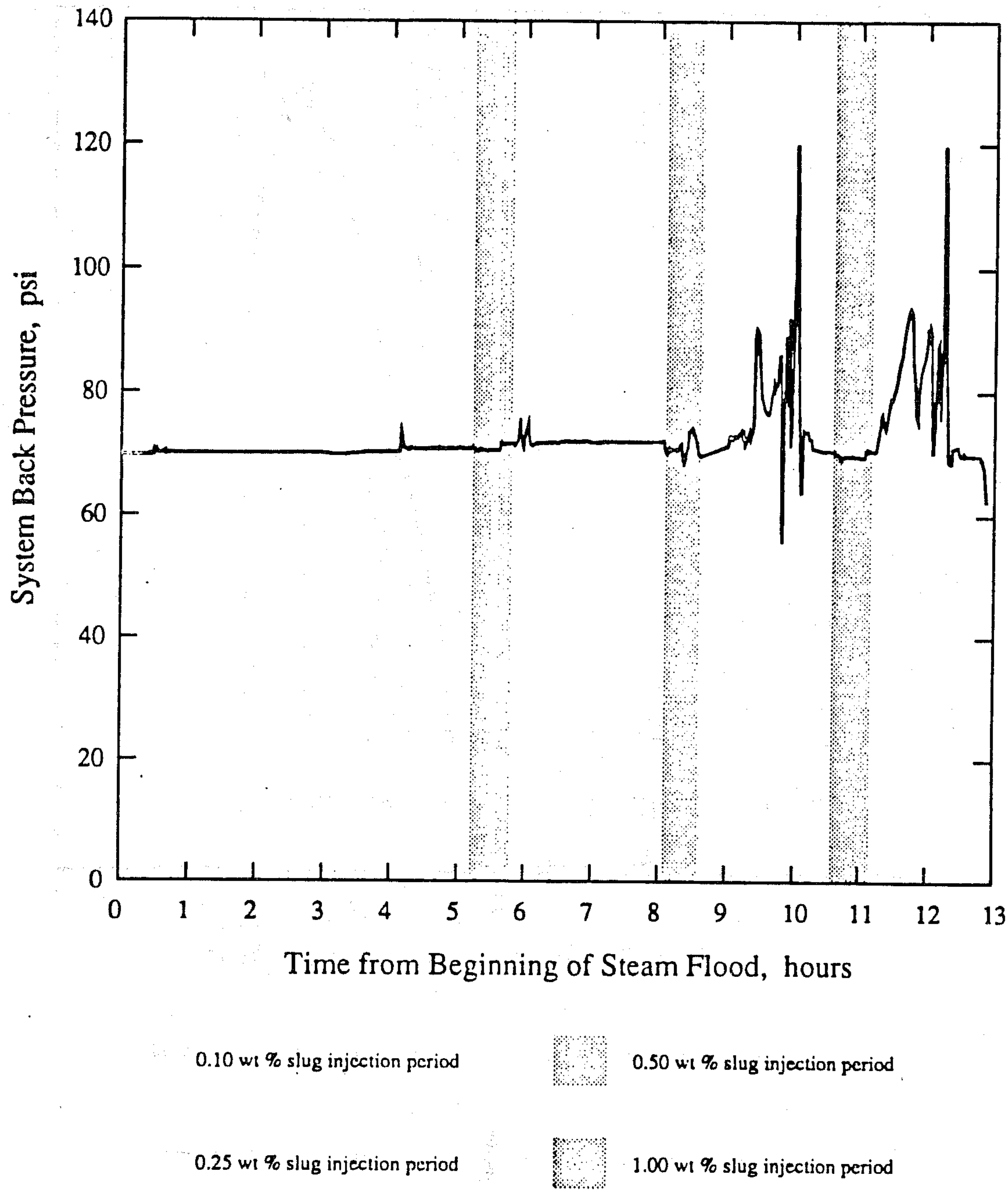

Figure 5.28 : System Back Pressure during Run 08

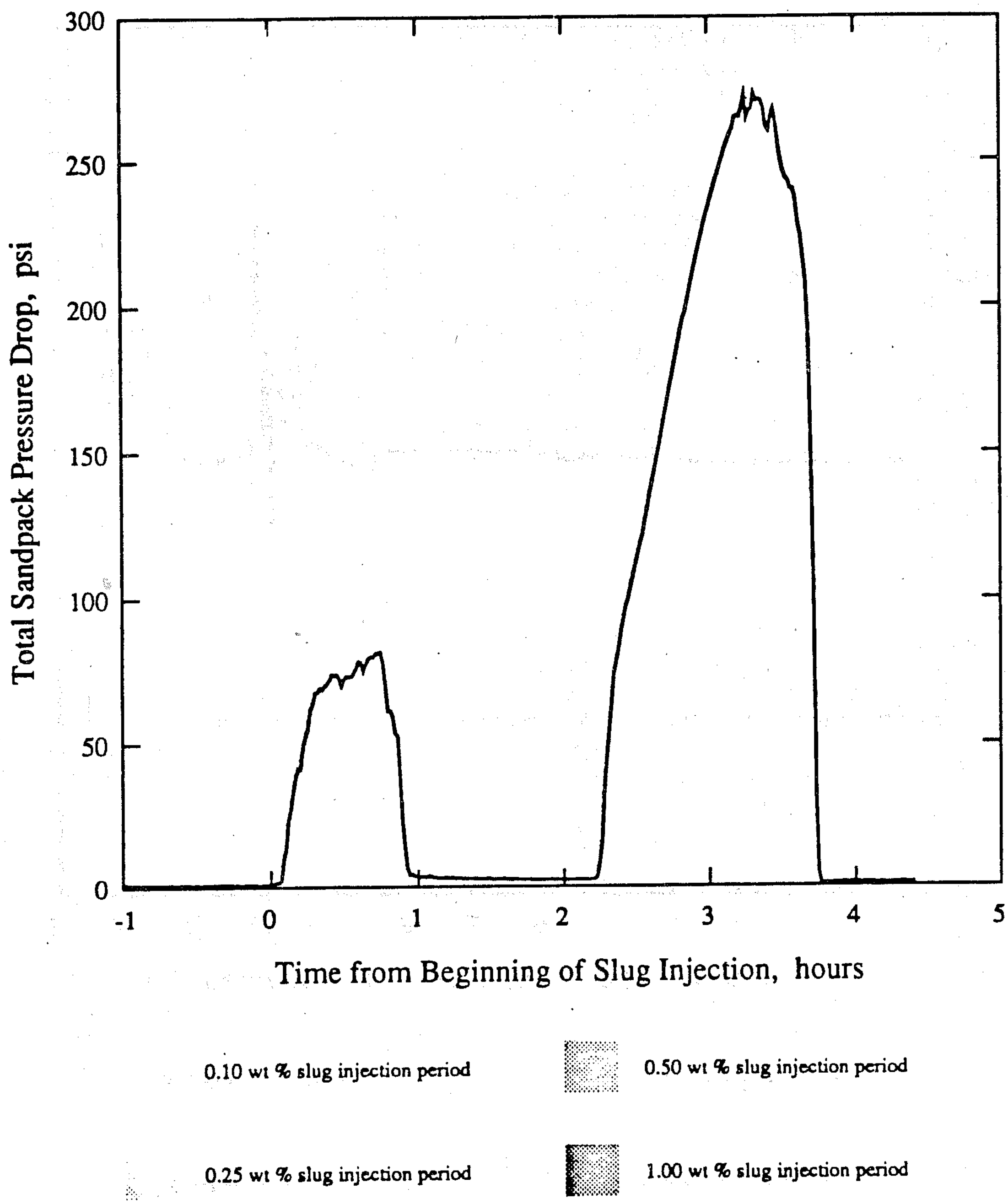

Figure 5.29 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet AOS 1618 - Run 10

peaking at 82 psi for the first slug (Table 5.5). The foam generated by the second slug was much stronger and resulted in a pressure drop that caused the pressure transducer in the fourth section to overrange (Figure 5.30). The foam generated by the second slug did not begin to collapse until nearly an hour after injection of the slug has stopped. It is also worthy to note that the foam persisted in the second section far longer in response to the second slug (86 minutes) than to the first slug (29 minutes). This increase in the pressure response duration for the second section is unusual. Difficulty was encountered in controlling the back pressure during the production of the foam (Figure 5.31).

Figures 5.32 to 5.34 and Table 5.6 present information concerning Run 30. As for Run 10, foam was generated in response to the injection of both surfactant slugs. However the pressure drop peaked at 132 psi in response to the injection of the first slug, compared to 82 psi for the first slug of Run 10. This relationship was reversed for the second slug as a peak of 247 psi was recorded for Run 30 compared to 272 psi for Run 10. The reason for these disagreements are not understood by the authors. It should be noted however that the curved plotted in Figure 5.33 compare favourably with those shown in Figure 5.30.

Figure 5.34 shows that during the aggressive generation of foam within the second section, there was a significant decrease in the system back pressure. The recorded pressure drop decreased from the set value of 70 psig to about 62 psig. The mechanism that lead to this decrease is discussed in Section 5.3 of this report.

5.3.8. Shell Enordet AOS 2024 (Runs 9, 21 and 25)

Three experiments were performed using Shell's Enordet AOS 2024 surfactant. During the first of these experiments, Run 9, three slugs of a 0.10 wt % solution were injected into the sandpack. After the experiment however, it was determined that the solution had not been prepared with enough care. At room temperature, the 31 wt % surfactant solution supplied by the manufacturer readily separates into two phases on standing. It is believed that during the preparation of the solution used in Run 9, the solution was insufficiently mixed resulting in the use of a sample of the surfactant that was not representative of the actual composition of the surfactant. Figure 5.35 shows the variation in the measured pressure drop across the length of the tube with time. It is believed that the significant improvement in the pressure drop generated between the second and third slugs was caused by replacing a clogged filter in the surfactant injection line. The 0.1 wt % solution that was prepared contained a lot of sediment that could not be dissolved, even at 120°F (50°C). These sediments and suspended solids clogged the filter protecting the surfactant injection pump. Between injection of the second and third surfactant slugs, the pump was observed to be discharging at a reduced rate. This suggested that the second slug could have been undersized. The filter was changed immediately prior to injection of the third slug. Because of the above difficulties, the observations of Run 9 are not considered further.

A second batch of Enordet AOS 2024 was received from Shell and was tested in Runs 21 and 25. (Run 25 was performed in the absence of nitrogen injection and is discussed in Section 5.4 of this report.) No difficulties were encountered in handling the surfactant once heat was applied to get it into solution.

The increase in the sandpack pressure drop in response to the injection of a single 0.10 wt % slug was so great that no further slugs of the surfactant were injected (Figure 5.36). This long-chain alpha-olefin sulphonate produced the strongest and most durable foam of all the surfactants tested at the lowest concentration of 0.10 wt %. The foam produced a pressure drop of 234 psi across the sandpack and persisted for 85 minutes (Table 5.7). Figure 5.37

Table 5.5 : Summary of Pressure Response Data for Shell Enordet AOS 1618 (Run 10)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	--	--
Slug Injection					
Start Time (hr)		5.095	7.289	--	--
Stop Time (hr)		5.685	7.881	--	--
Duration (min)		35.4	35.5	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	43.2	52.3	--	--
	Time (hr)	5.31	7.40	--	--
Section 2	ΔP_2 (psi)	51.5	62.6	--	--
	Time (hr)	5.46	7.69	--	--
Section 3	ΔP_3 (psi)	72.8	113.0	--	--
	Time (hr)	5.76	8.45	--	--
Section 4	ΔP_4 (psi)	48.0	> 132 ‡	--	--
	Time (hr)	5.92	? ‡	--	--
Entire Tube	ΔP (psi)	81.6	> 272.3 ‡	--	--
	Time (hr)	5.84	8.35	--	--
Duration of Pressure Response†					
Section 1	Time (min)	37	24	--	--
Section 2	Time (min)	29	86	--	--
Section 3	Time (min)	33	80	--	--
Section 4	Time (min)	16	68	--	--
Entire Tube	Time (min)	56	92	--	--
Response Time Lag (min)		4	2	--	--

† Duration of pressure response as defined in Section 5.2.

‡ Transducers overranged during slug injection.

Table 5.6 : Summary of Pressure Response Data for Shell Enordet AOS1618 (Run 30)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	--	--
Slug Injection					
Start Time (hr)		5.146	7.341	--	--
Stop Time (hr)		5.736	7.931	--	--
Duration (min)		35.4	35.4	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	50.0	45.0	--	--
	Time (hr)	5.33	7.46	--	--
Section 2	ΔP_2 (psi)	66.4	64.4	--	--
	Time (hr)	5.46	7.88	--	--
Section 3	ΔP_3 (psi)	88.8	102.1	--	--
	Time (hr)	5.89	8.26	--	--
Section 4	ΔP_4 (psi)	90.9	127.0	--	--
	Time (hr)	6.19	8.46	--	--
Entire Tube	ΔP (psi)	131.9	247.2	--	--
	Time (hr)	5.99	8.31	--	--
Duration of Pressure Response†					
Section 1	Time (min)	35	44	--	--
Section 2	Time (min)	42	69	--	--
Section 3	Time (min)	52	73	--	--
Section 4	Time (min)	35	61	--	--
Entire Tube	Time (min)	68	86	--	--
Response Time Lag (min)		3	1	--	--

† Duration of pressure response as defined in Section 5.2.

Table 5.7 : Summary of Pressure Response Data for Shell Enordet AOS2024 (Run 21)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	--	--	--
Slug Injection					
Start Time (hr)		4.999	--	--	--
Stop Time (hr)		5.591	--	--	--
Duration (min)		35.5	--	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	51.8	--	--	--
	Time (hr)	5.19	--	--	--
Section 2	ΔP_2 (psi)	53.8	--	--	--
	Time (hr)	5.37	--	--	--
Section 3	ΔP_3 (psi)	93.7	--	--	--
	Time (hr)	6.14	--	--	--
Section 4	ΔP_4 (psi)	118.4	--	--	--
	Time (hr)	6.08	--	--	--
Entire Tube	ΔP (psi)	233.7	--	--	--
	Time (hr)	6.08	--	--	--
Duration of Pressure Response†					
Section 1	Time (min)	81	--	--	--
Section 2	Time (min)	75	--	--	--
Section 3	Time (min)	71	--	--	--
Section 4	Time (min)	58	--	--	--
Entire Tube	Time (min)	85	--	--	--
Response Time Lag (min)		4	--	--	--

† Duration of pressure response as defined in Section 5.2.

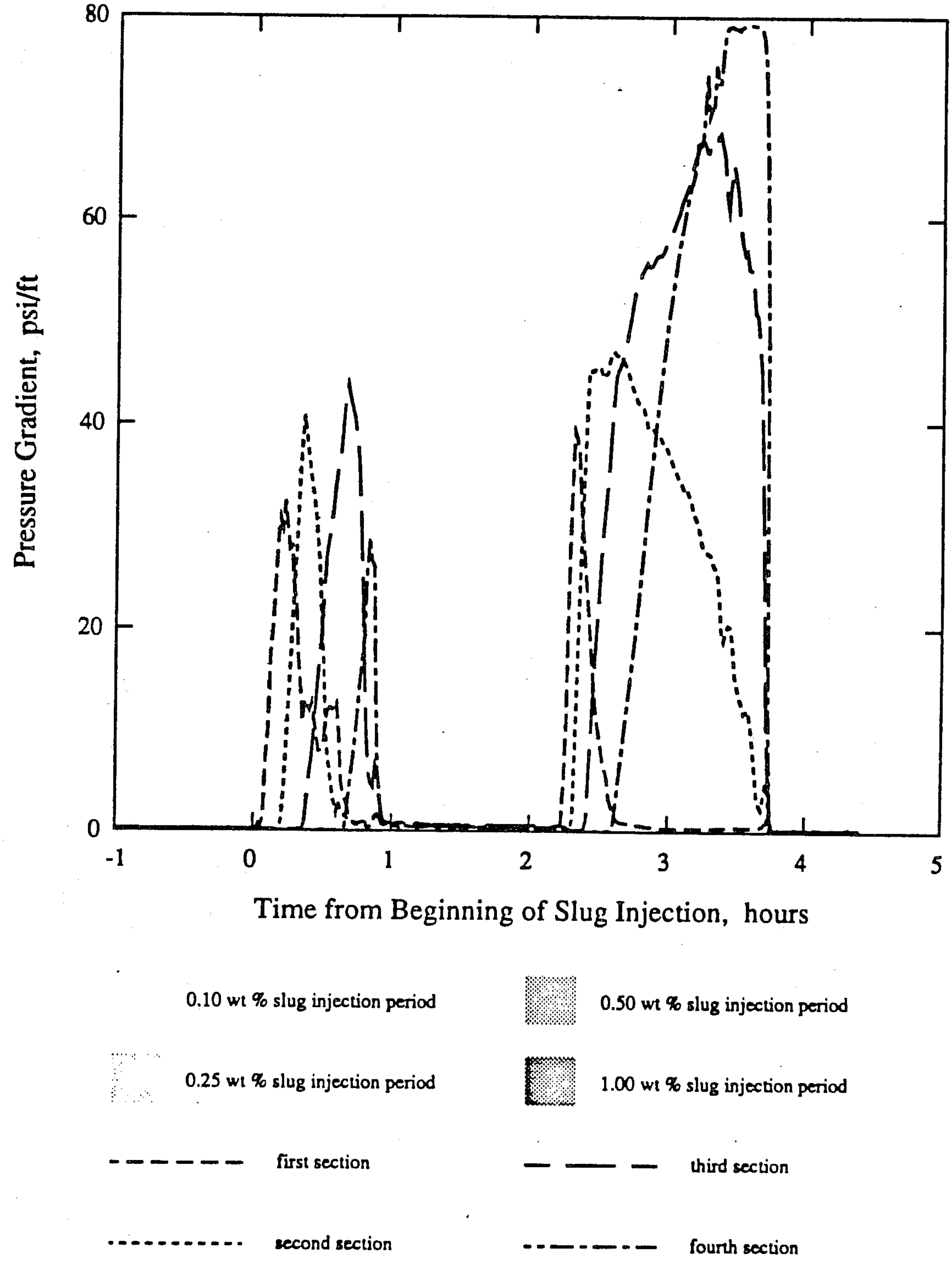

Figure 5.30 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet AOS 1618 - Run 10

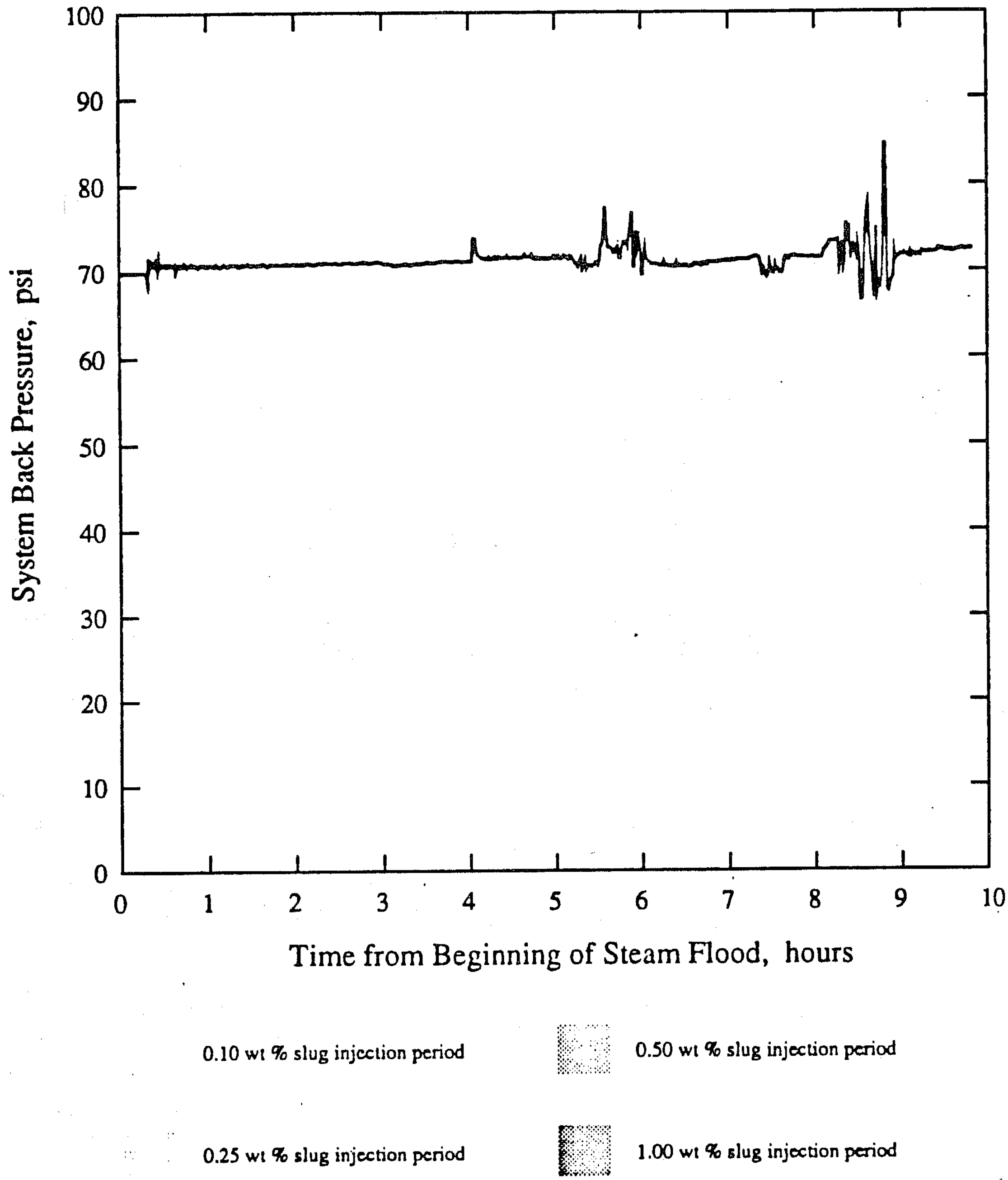

Figure 5.31 : System Back Pressure during Run 10

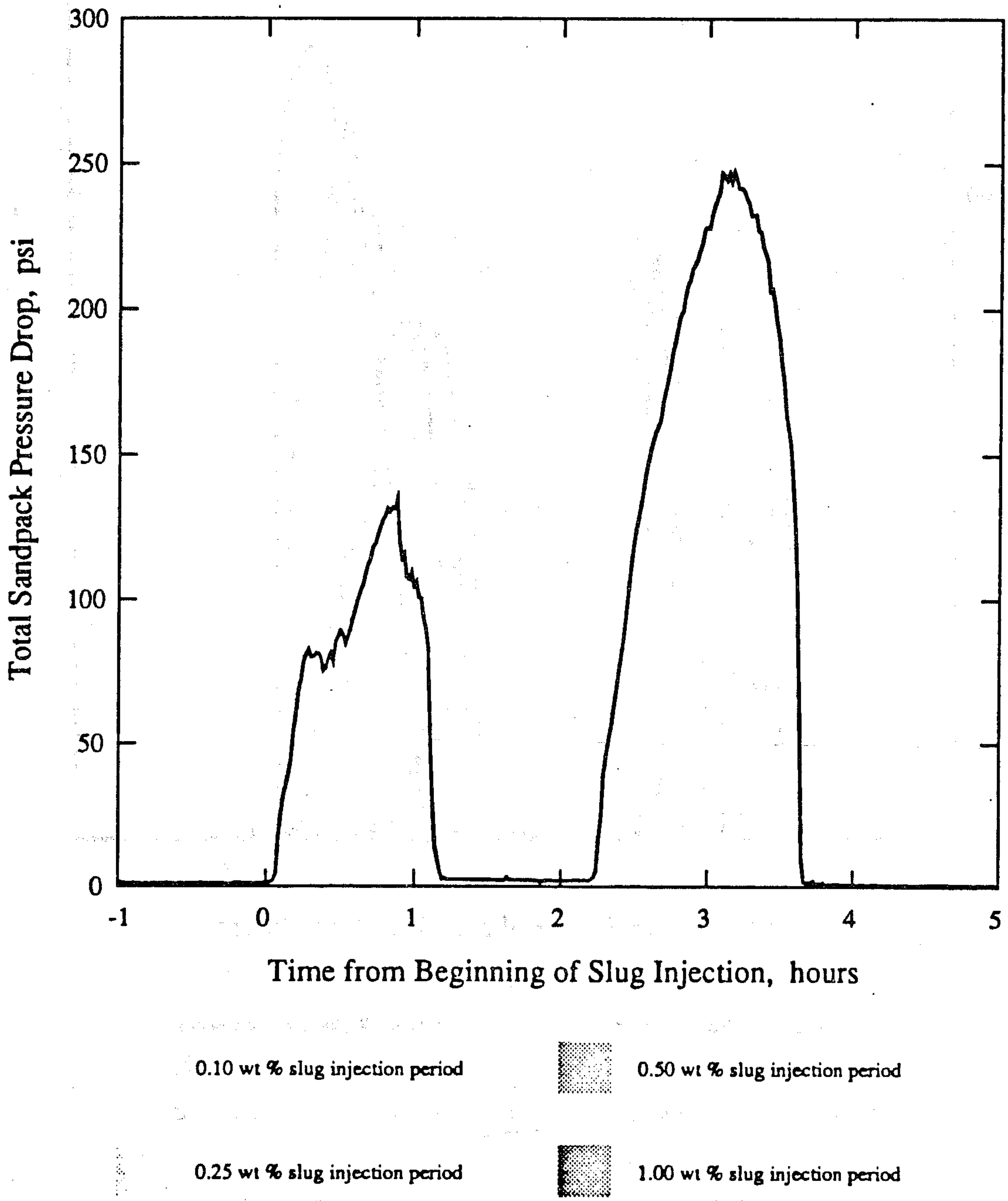

Figure 5.32 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet AOS 1618 - Run 30

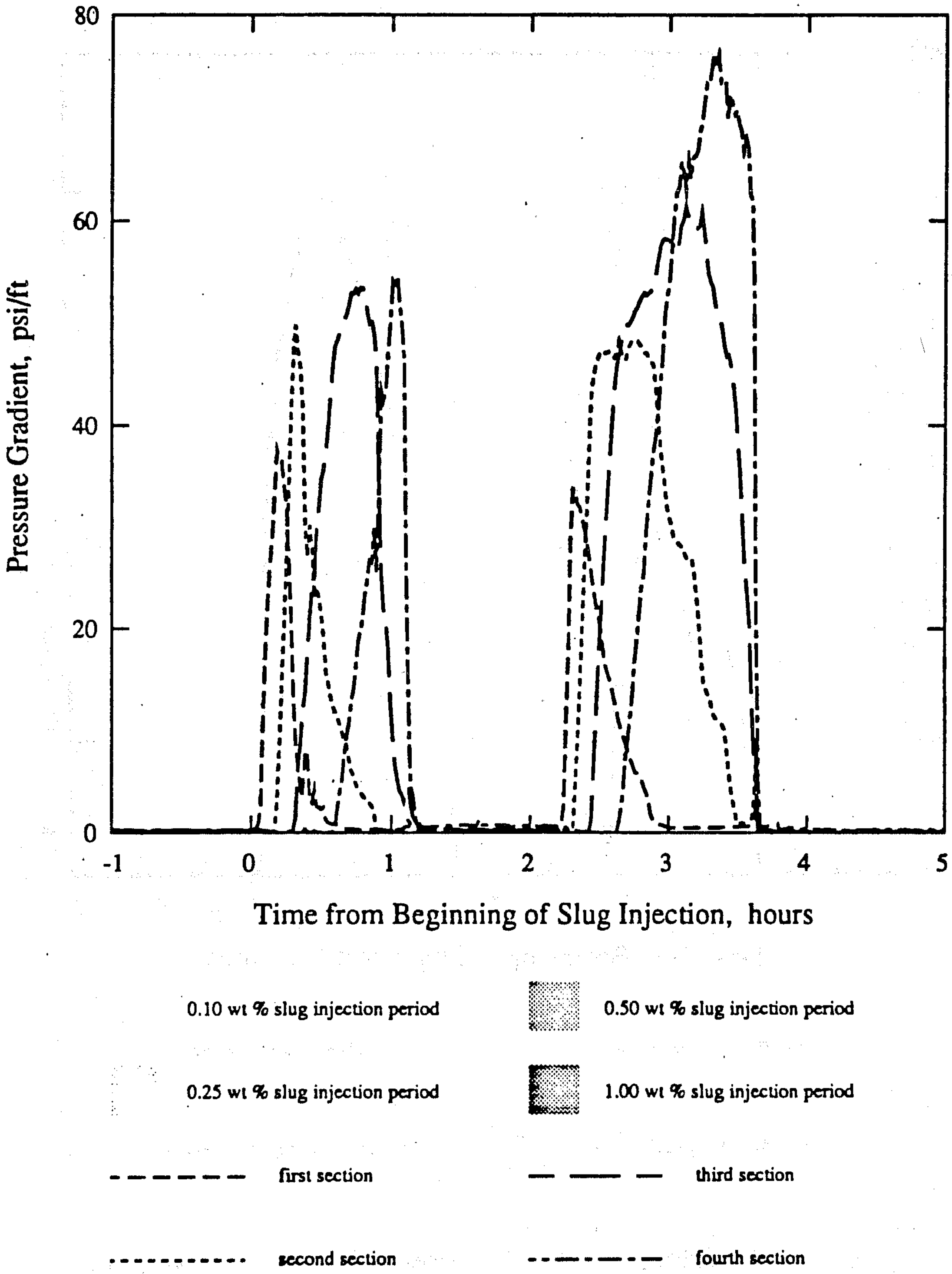

Figure 5.33 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet AOS 1618 - Run 30

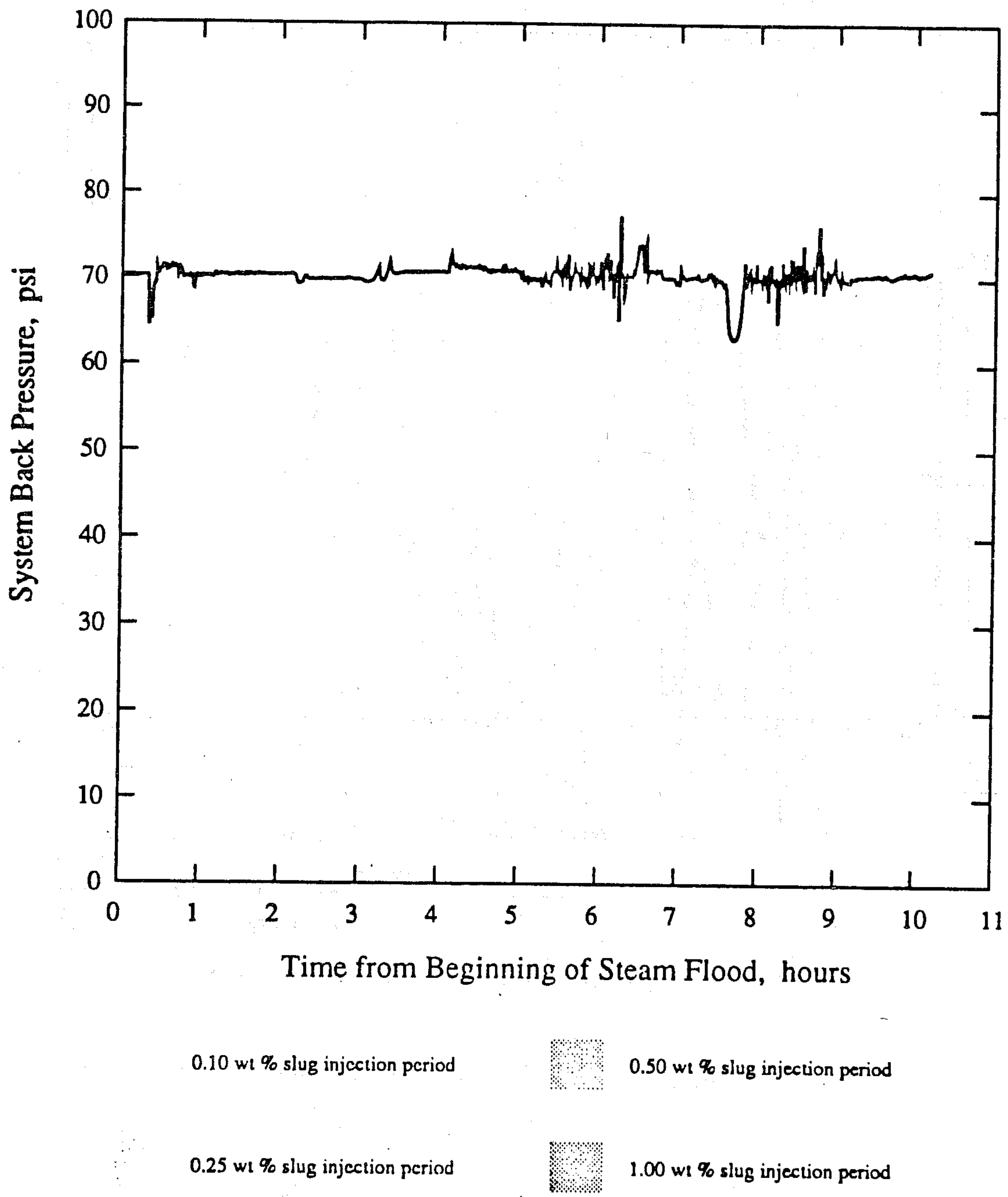

Figure 5.34 : System Back Pressure during Run 30

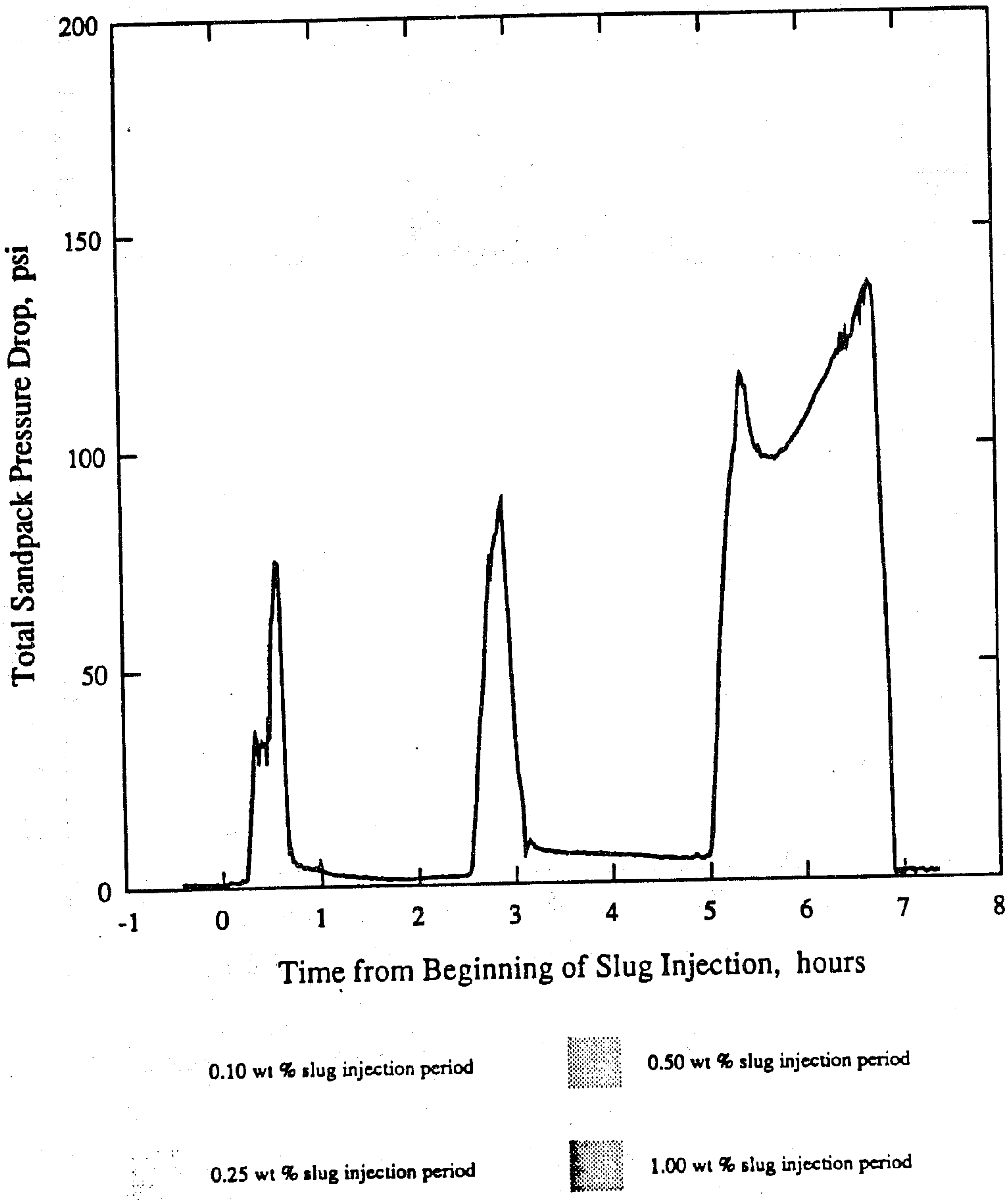

Figure 5.35 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet AOS 2024 - Run 09

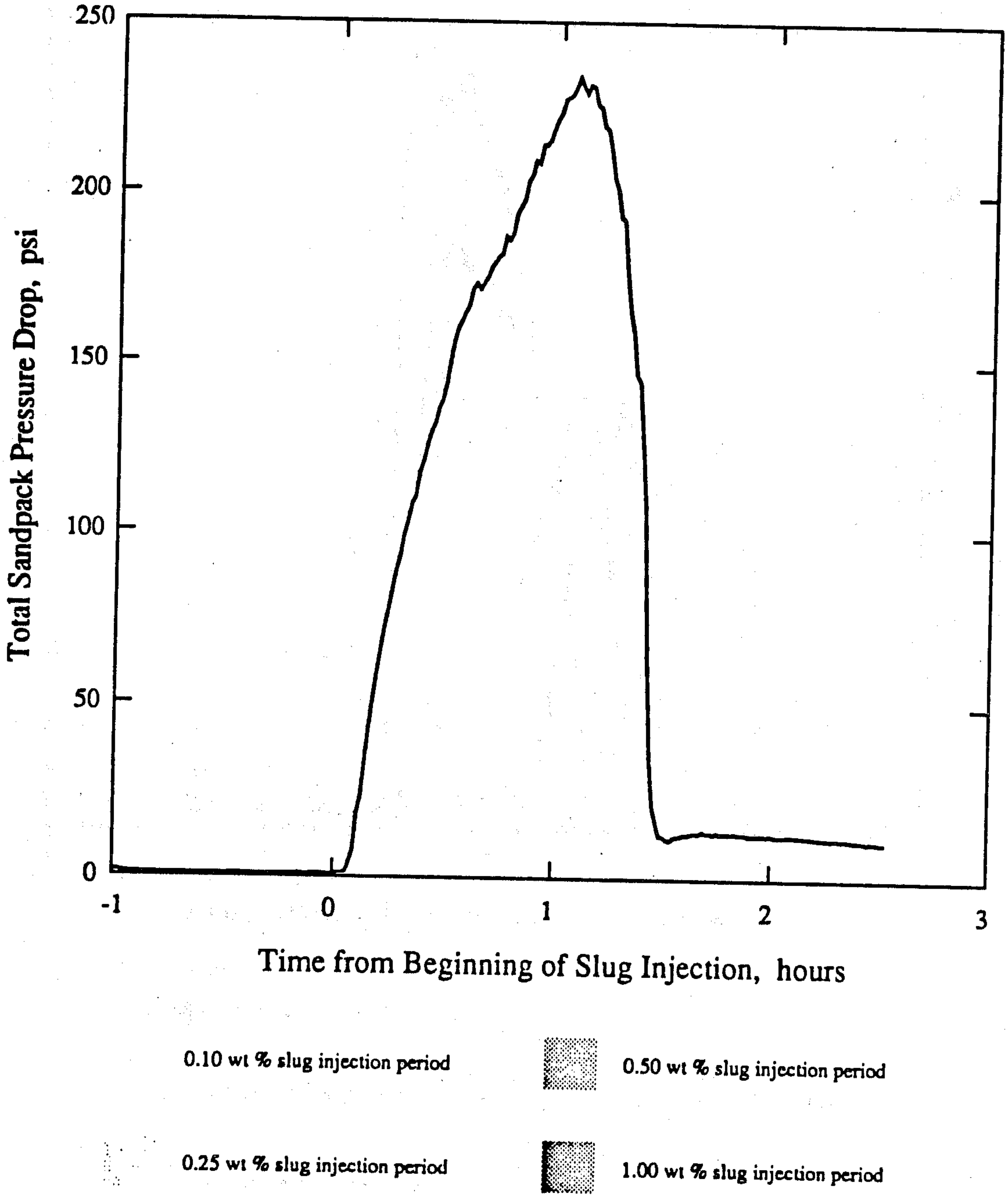

Figure 5.36 : Total Pressure Drop Response to Injection of One Slug of Shell Enordet AOS 2024 - Run 21

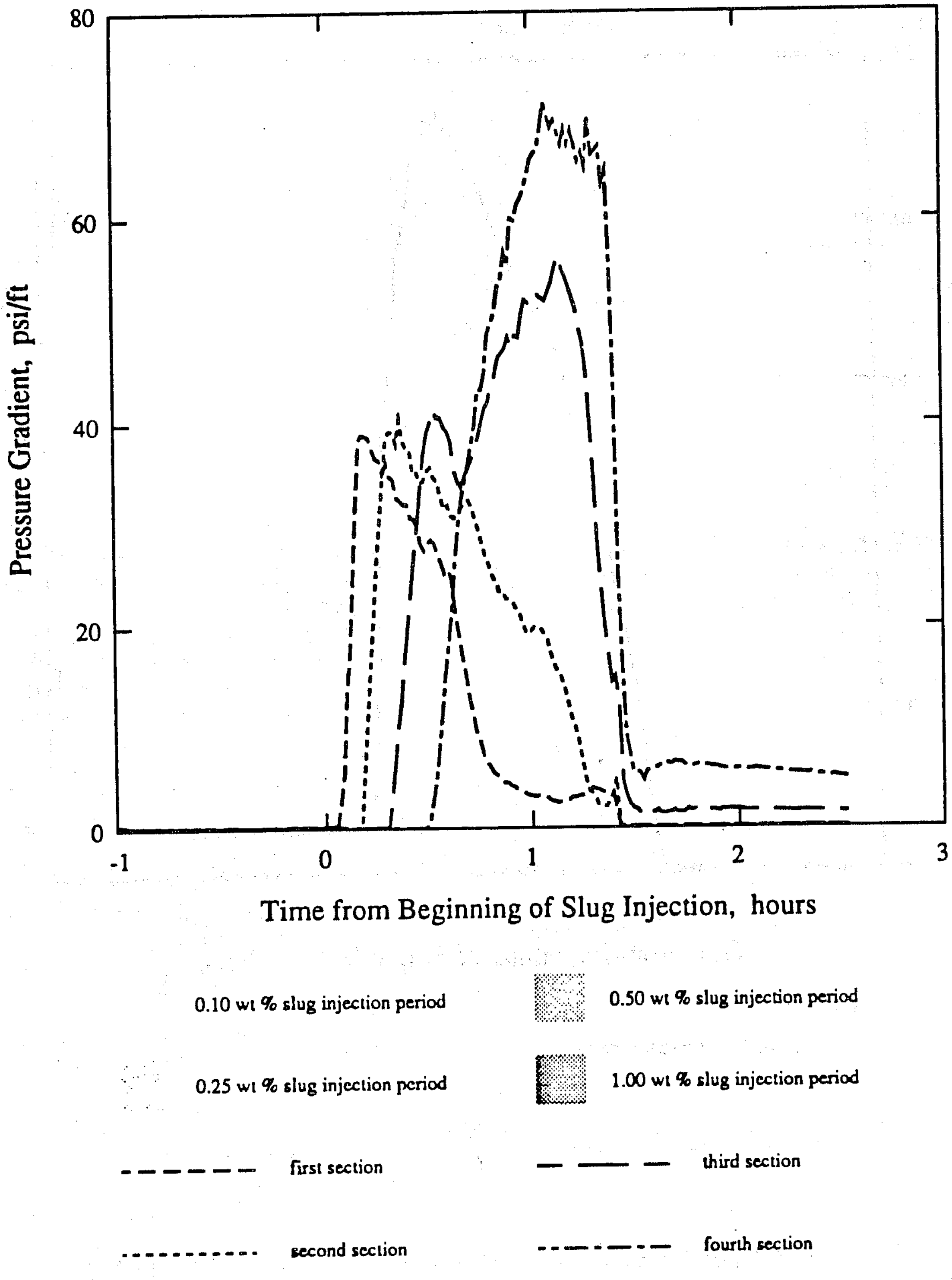

Figure 5.37 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of One Slug of Shell Enordet AOS 2024 - Run 21

shows that the foam was present in all four sandpack sections with the strongest foam being generated in the downstream section. The system back pressure was fairly constant with only significant variations occurring during the period of manual control while foam was being produced (Figure 5.38).

5.3.9. Shell Enordet IOS 1517 (Run 13)

Shell's internal olefin sulphonate surfactant, Enordet IOS 1517 was studied during Run 13. Initially, a 0.10 wt % slug of the surfactant was injected into the sandpack, but when no pressure response was observed, a second slug at 0.25 wt % was injected. This did not elicit a response, so a 0.50 wt % slug was injected which finally yielded an increase in the sandpack's pressure drop (Figure 5.39). A maximum pressure drop of 161 psi was recorded during the pressure response which lasted for 100 minutes (Table 5.8). Foaming occurred in all four sections of the sandpack (Figure 5.40) but the foam was not sustained for very long in the first two sections. Figure 5.41 shows that the system back pressure was maintained close to 70 psig throughout most of the experiment.

5.3.10. Shell Enordet IOS 1720 (Runs 11 and 22)

Two experiments were performed using Shell's Enordet IOS 1720 surfactant. During Run 11, two slugs of a 0.1 wt % solution were injected into the sandpack, followed by the injection of a 1.0 wt % slug. While foaming was not observed in response to the first two slugs, strong foaming occurred immediately the third surfactant slug was injected (Figure 5.42). The strong foam persisted for 148 minutes, including 118 minutes after injection of the surfactant had stopped (Table 5.9). Again, the foam was so strong that the pressure drop generated in the sandpack's fourth section caused the pressure transducer to overrange (Figure 5.43). Because of this the recorded maximum pressure drop across the sandpack of 224 psi was probably exceeded significantly. Figure 5.44 shows that the system back pressure varied significantly from 70 psig due to the production of foam. This run was performed before the installation of a system allowing manual back pressure control.

Run 22 began with the injection of a 0.10 wt % slug. When no pressure response was observed a 0.25 wt slug was injected. After an eight minute delay period the pressure drop across the sandpack began to increase. Figure 5.45 shows that the pressure drop increased to 217 psi, and that the pressure response lasted for 79 minutes (Table 5.10). Figure 5.46 clearly shows that foaming was present in all four sections of the sandpack following the injection of the second slug. The plot of back pressure versus time presented in Figure 5.47 shows that some problems were again encountered controlling the system back pressure during the production of foam.

A comparison of the pressure responses to the injection of the 0.25 wt % slug (Figure 5.45) and the 1.0 wt % slug (Figure 5.42) shows that the more concentrated solution resulted in a pressure drop of both a greater magnitude and concentration. (When comparing the diagrams, note the compressed time scale of Figure 5.42.) Also, the time delay between the surfactant injection and the onset of foaming was much less for the more concentrated solution.

5.3.11. Shell Enordet IOS 2024 (Runs 16 and 24)

The foam forming ability of Shell's Enordet IOS 2024 surfactant was studied during Runs 16 and 24. In the first of these runs a single 0.10 wt % slug was followed by the

Table 5.8 : Summary of Pressure Response Data for Shell Enordet IOS1517 (Run 13)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	0.50	--
Slug Injection					
Start Time (hr)		5.126	6.933	8.705	--
Stop Time (hr)		5.716	7.523	9.300	--
Duration (min)		35.4	35.4	35.7	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	--	43.7	--
	Time (hr)	--	--	8.86	--
Section 2	ΔP_2 (psi)	--	--	46.4	--
	Time (hr)	--	--	8.95	--
Section 3	ΔP_3 (psi)	--	--	63.5	--
	Time (hr)	--	--	9.80	--
Section 4	ΔP_4 (psi)	--	--	105.5	--
	Time (hr)	--	--	10.10	--
Entire Tube	ΔP (psi)	--	--	161.0	--
	Time (hr)	--	--	9.98	--
Duration of Pressure Response†					
Section 1	Time (min)	--	--	14	--
Section 2	Time (min)	--	--	38	--
Section 3	Time (min)	--	--	87	--
Section 4	Time (min)	--	--	75	--
Entire Tube	Time (min)	--	--	100	--
Response Time Lag (min)		--	--	6	--

† Duration of pressure response as defined in Section 5.2.

Table 5.9 : Summary of Pressure Response Data for Shell Enordet IOS1720 (Run 11)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	1.00	--
Slug Injection					
Start Time (hr)		4.924	6.531	8.195	--
Stop Time (hr)		5.531	7.122	8.794	--
Duration (min)		35.4	35.4	36.0	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	--	48.6	--
	Time (hr)	--	--	8.31	--
Section 2	ΔP_2 (psi)	--	--	54.8	--
	Time (hr)	--	--	8.48	--
Section 3	ΔP_3 (psi)	--	--	92.8	--
	Time (hr)	--	--	9.70	--
Section 4	ΔP_4 (psi)	--	--	> 120 ‡	--
	Time (hr)	--	--	? ‡	--
Entire Tube	ΔP (psi)	--	--	> 224 ‡	--
	Time (hr)	--	--	? ‡	--
Duration of Pressure Response†					
Section 1	Time (min)	--	--	28	--
Section 2	Time (min)	--	--	90	--
Section 3	Time (min)	--	--	131	--
Section 4	Time (min)	--	--	128	--
Entire Tube	Time (min)	--	--	148	--
Response Time Lag (min)		--	--	6	--

† Duration of pressure response as defined in Section 5.2.

‡ Transducers overranged during slug injection.

Table 5.10 : Summary of Pressure Response Data for Shell Enordet IOS1720 (Run 22)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	--	--
Slug Injection					
Start Time (hr)		5.008	6.759	--	--
Stop Time (hr)		5.599	7.349	--	--
Duration (min)		35.4	35.4	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	44.9	--	--
	Time (hr)	--	6.95	--	--
Section 2	ΔP_2 (psi)	--	54.8	--	--
	Time (hr)	--	7.16	--	--
Section 3	ΔP_3 (psi)	--	91.7	--	--
	Time (hr)	--	7.70	--	--
Section 4	ΔP_4 (psi)	--	100.2	--	--
	Time (hr)	--	7.95	--	--
Entire Tube	ΔP (psi)	--	217.1	--	--
	Time (hr)	--	7.70	--	--
Duration of Pressure Response†					
Section 1	Time (min)	--	41	--	--
Section 2	Time (min)	--	57	--	--
Section 3	Time (min)	--	69	--	--
Section 4	Time (min)	--	62	--	--
Entire Tube	Time (min)	--	79	--	--
Response Time Lag (min)		--	8	--	--

† Duration of pressure response as defined in Section 5.2.

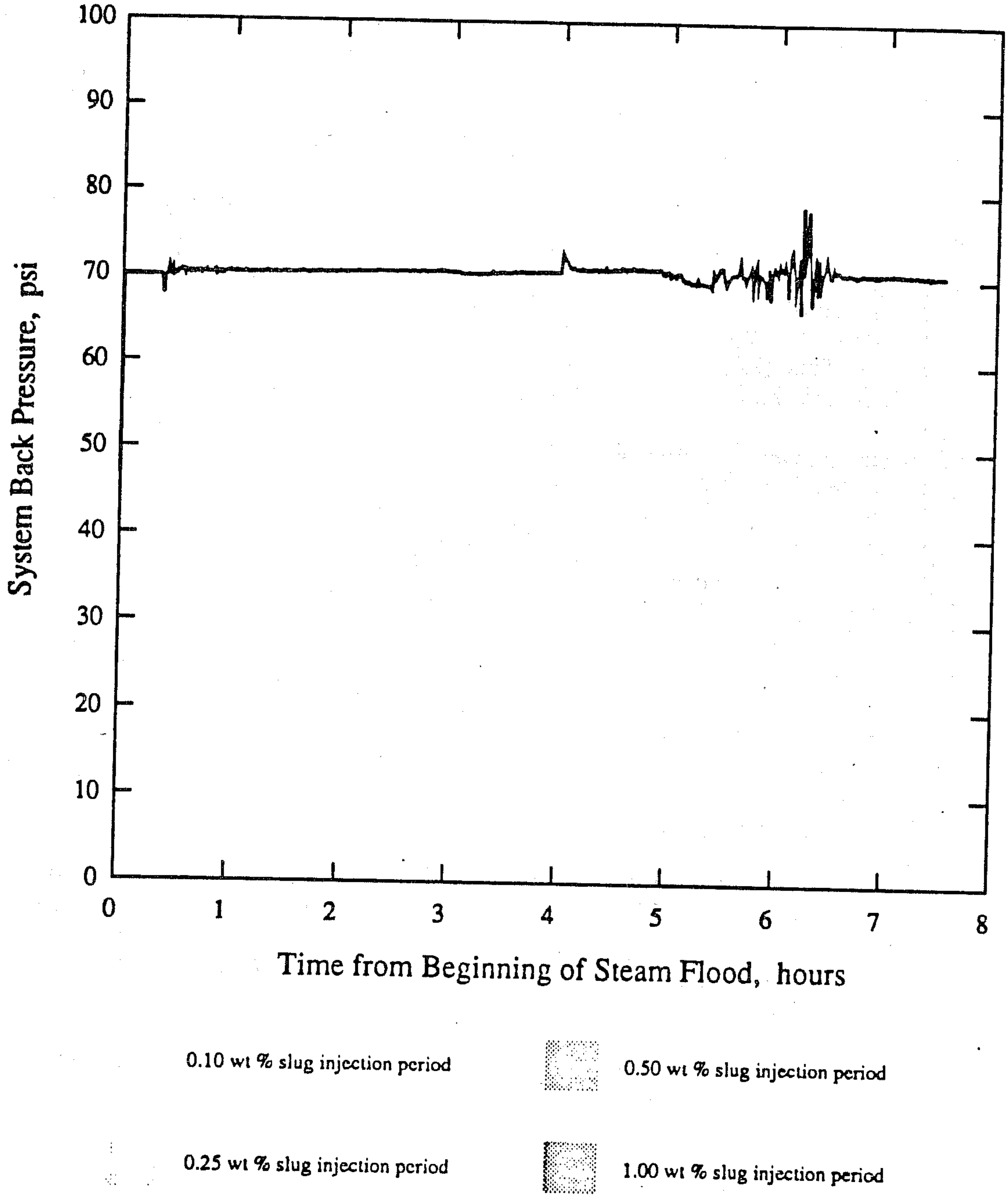

Figure 5.38 : System Back Pressure during Run 21

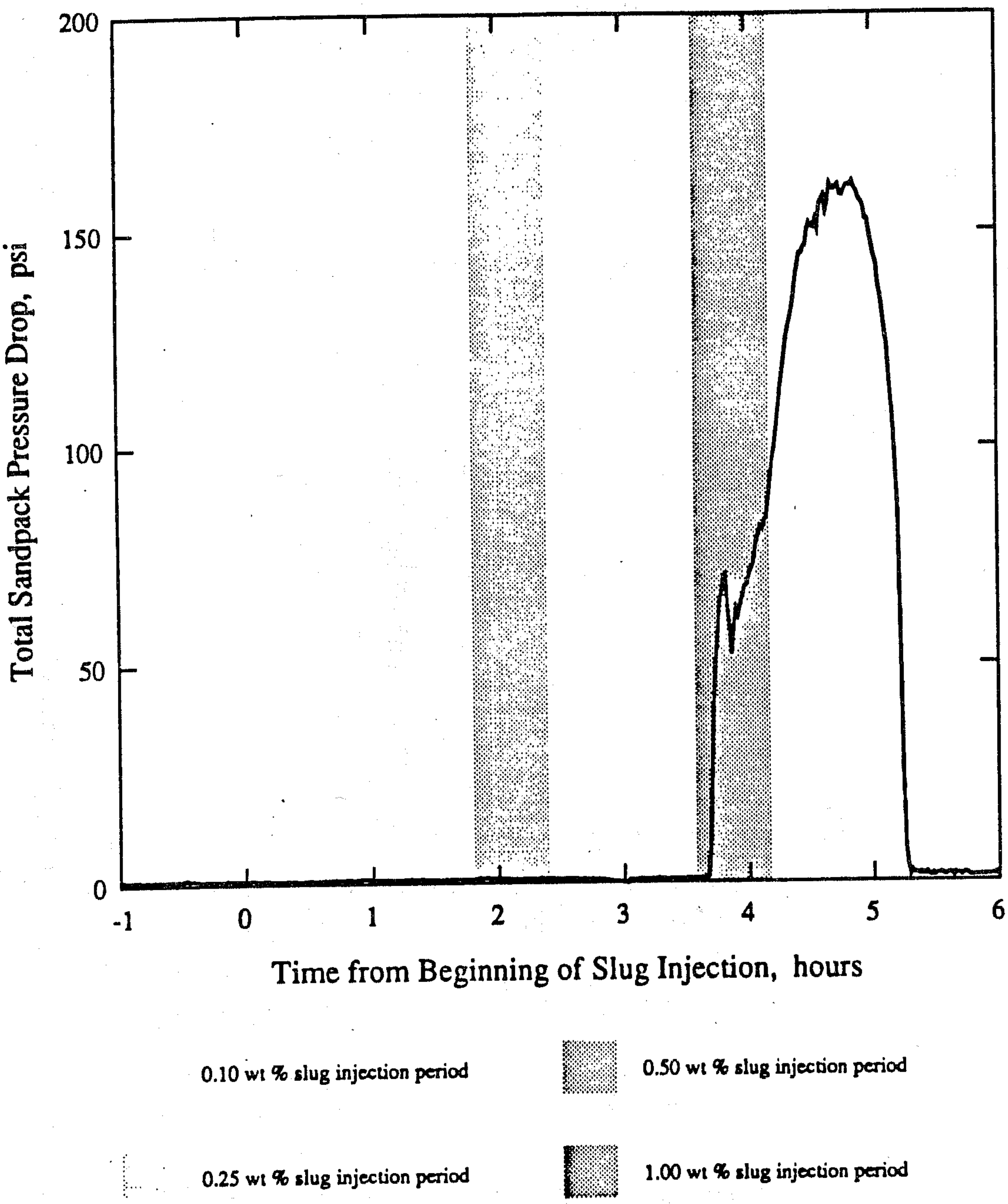

Figure 5.39 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet IOS 1517 - Run 13

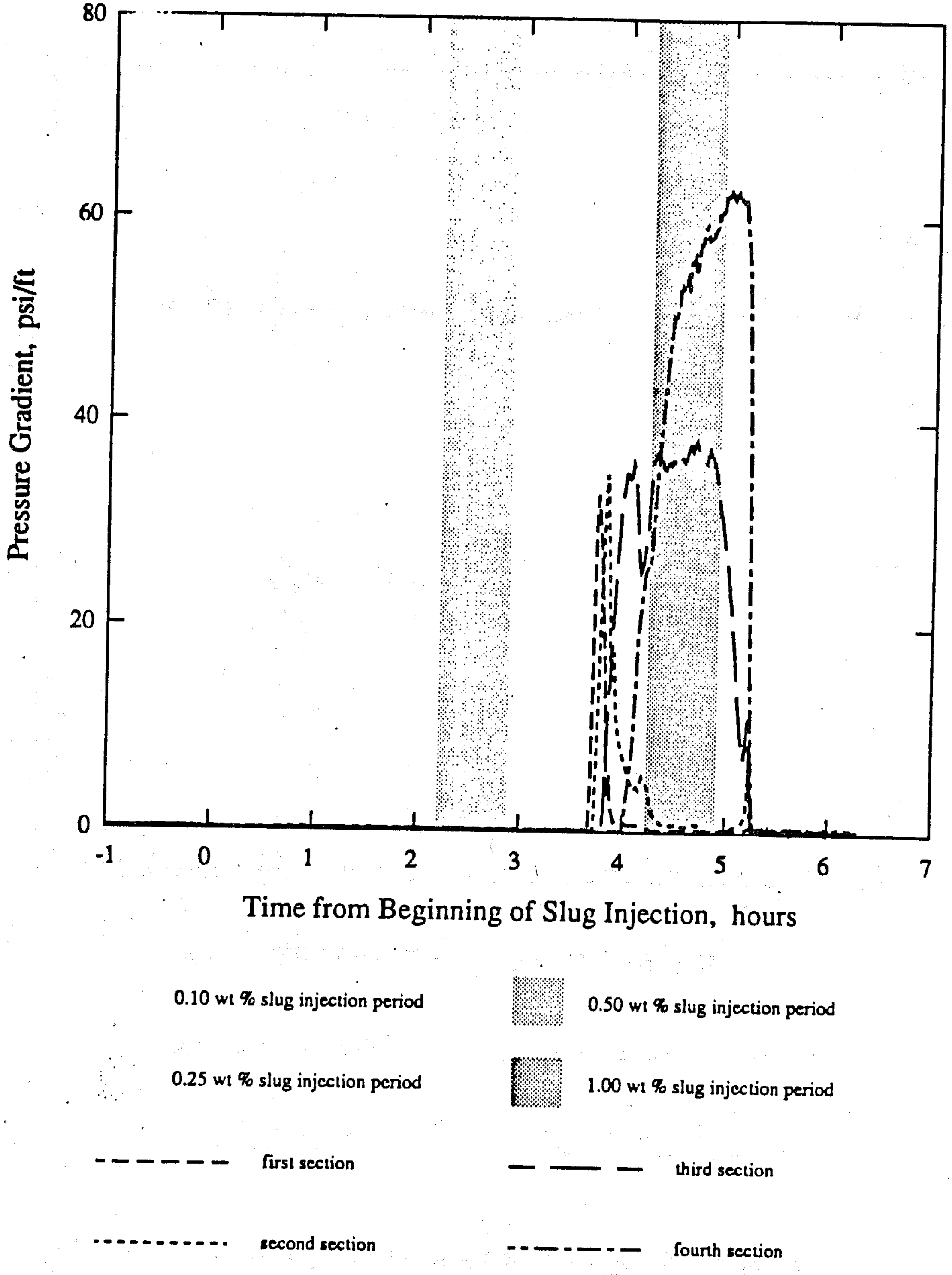

Figure 5.40 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Shell Enordet IOS 1517 - Run 13

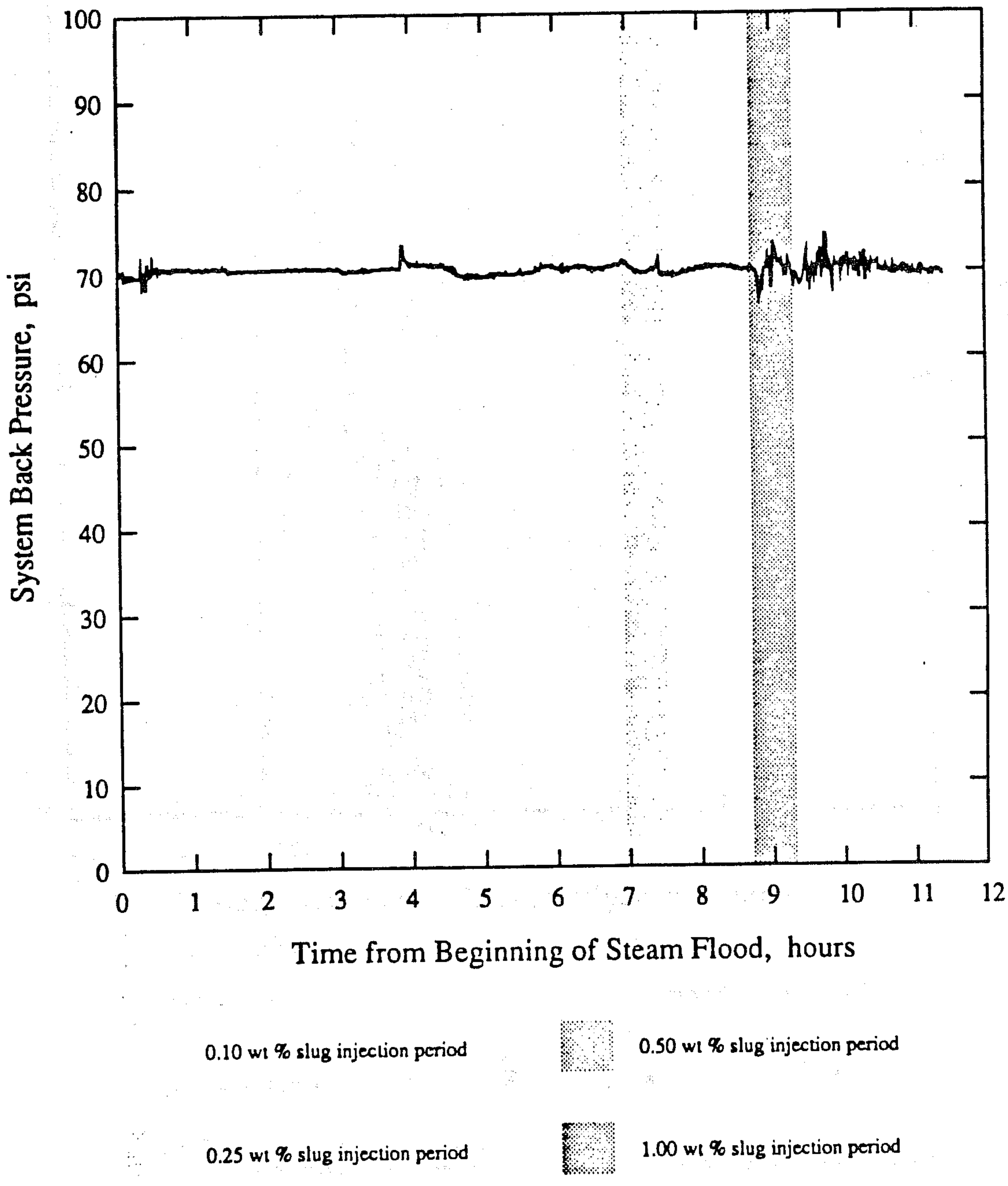

Figure 5.41 : System Back Pressure during Run 13

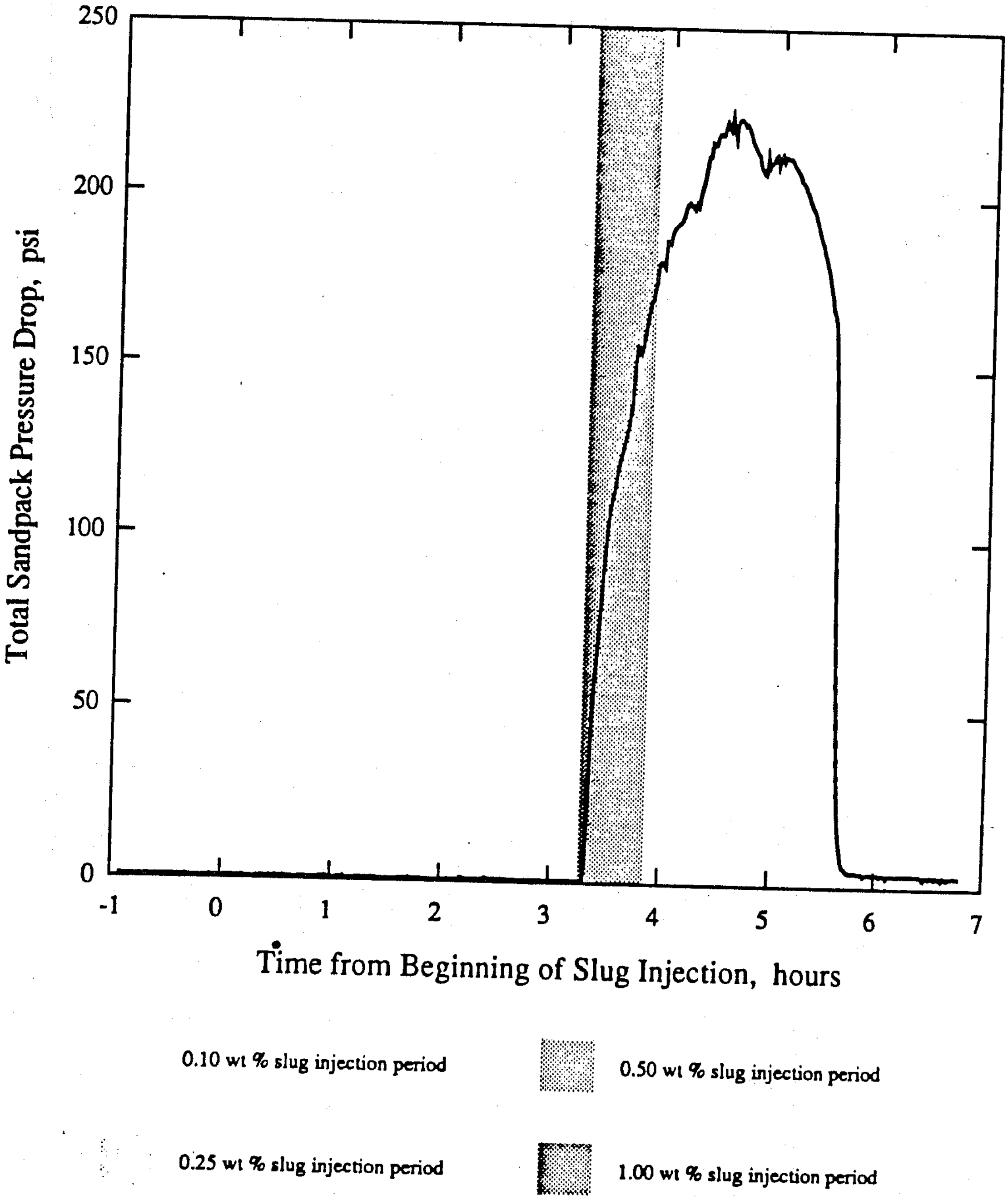

Figure 5.42 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet IOS 1720 - Run 11

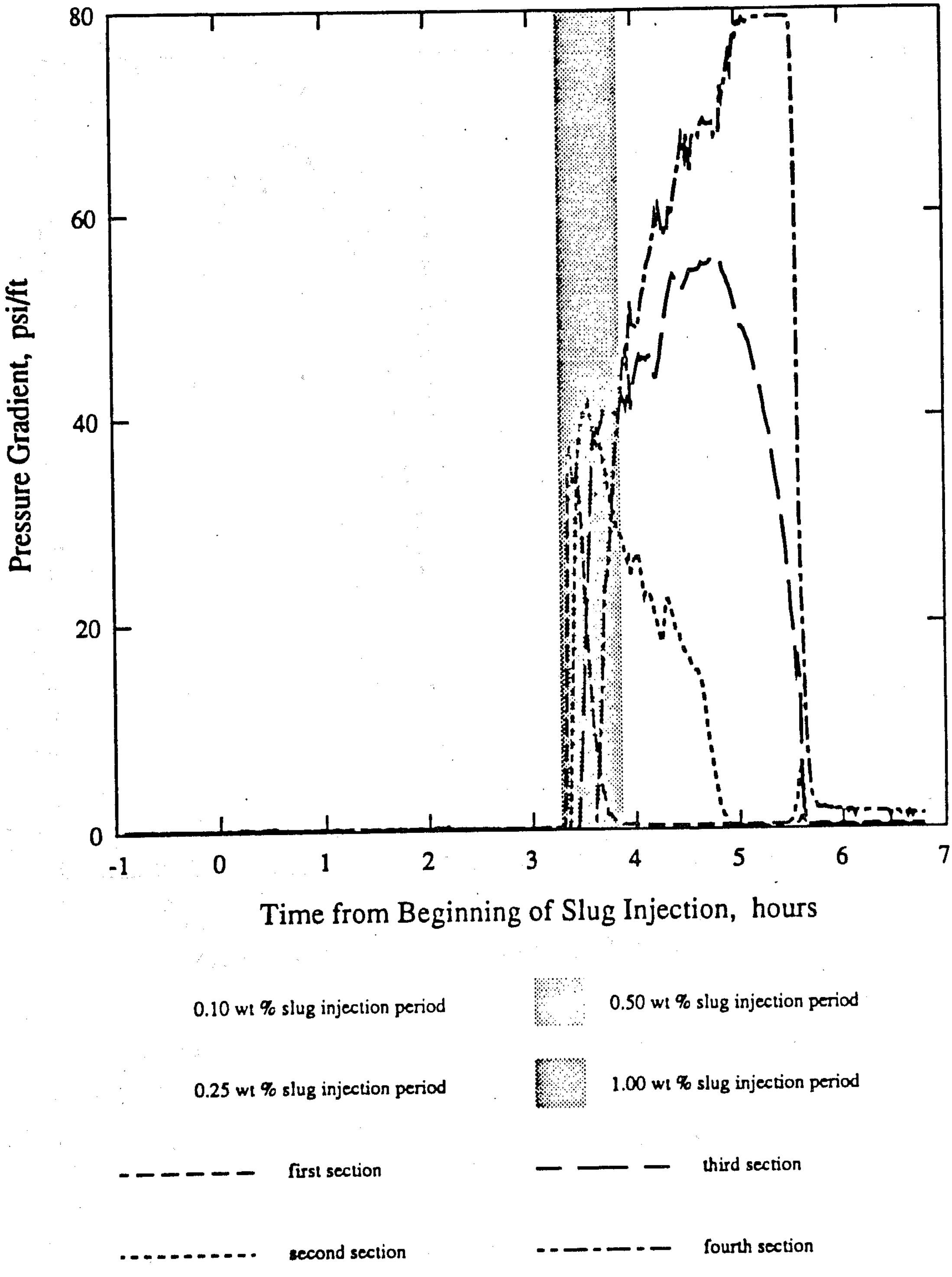

Figure 5.43 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Shell Enordet IOS 1720 - Run 11

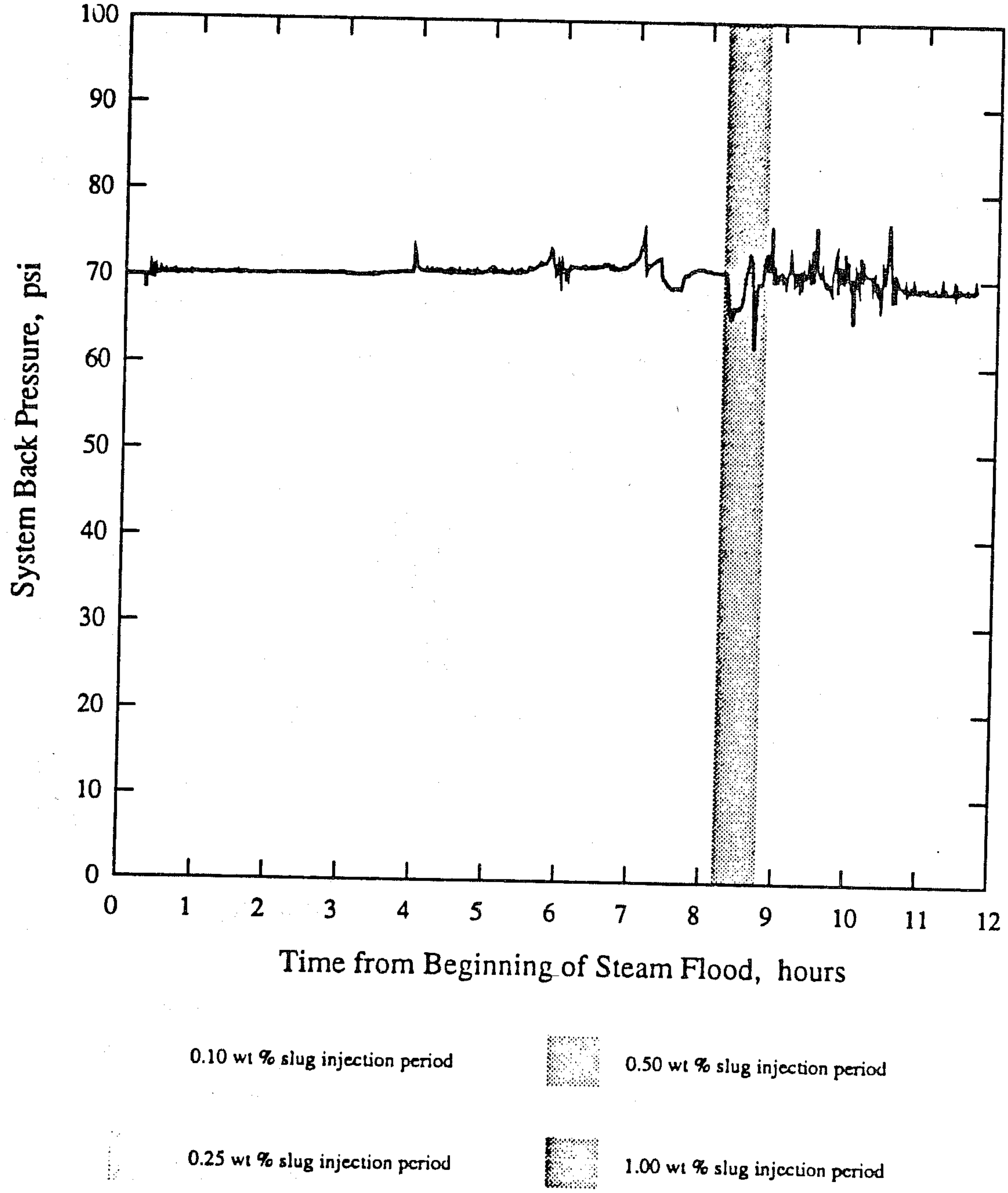

Figure 5.44 : System Back Pressure during Run 11

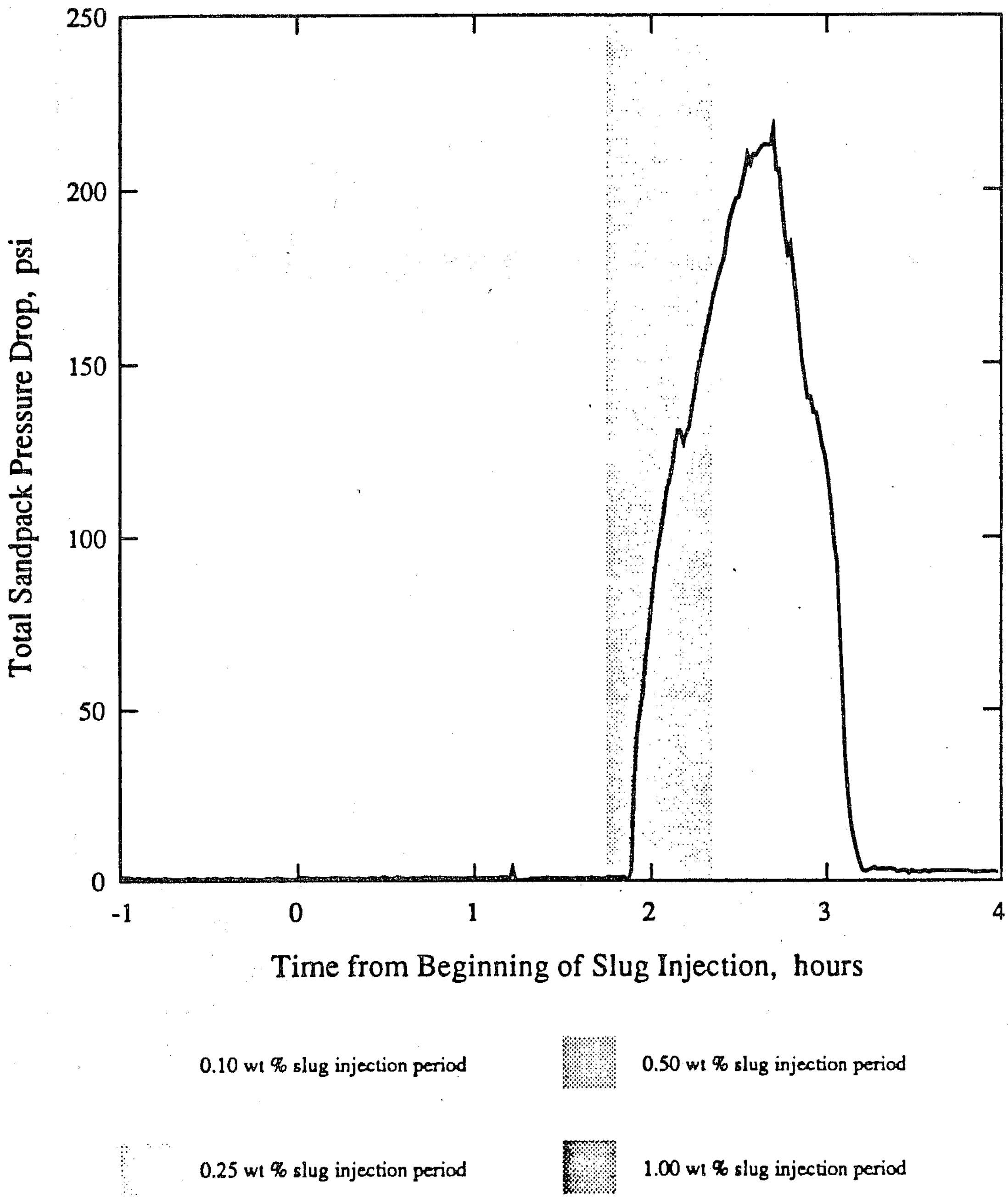

Figure 5.45 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet IOS 1720 - Run 22

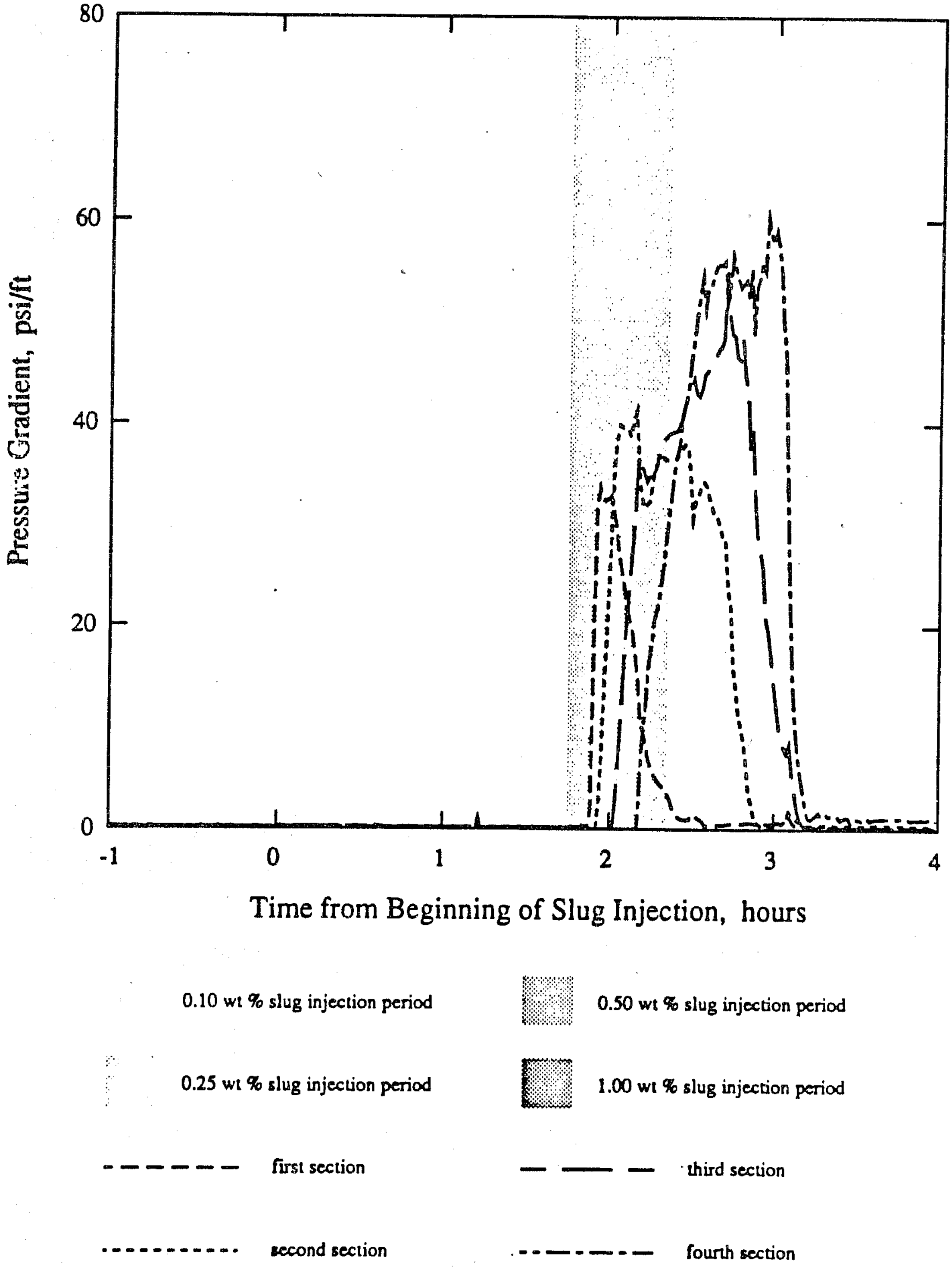

Figure 5.46 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet IOS 1720 - Run 22

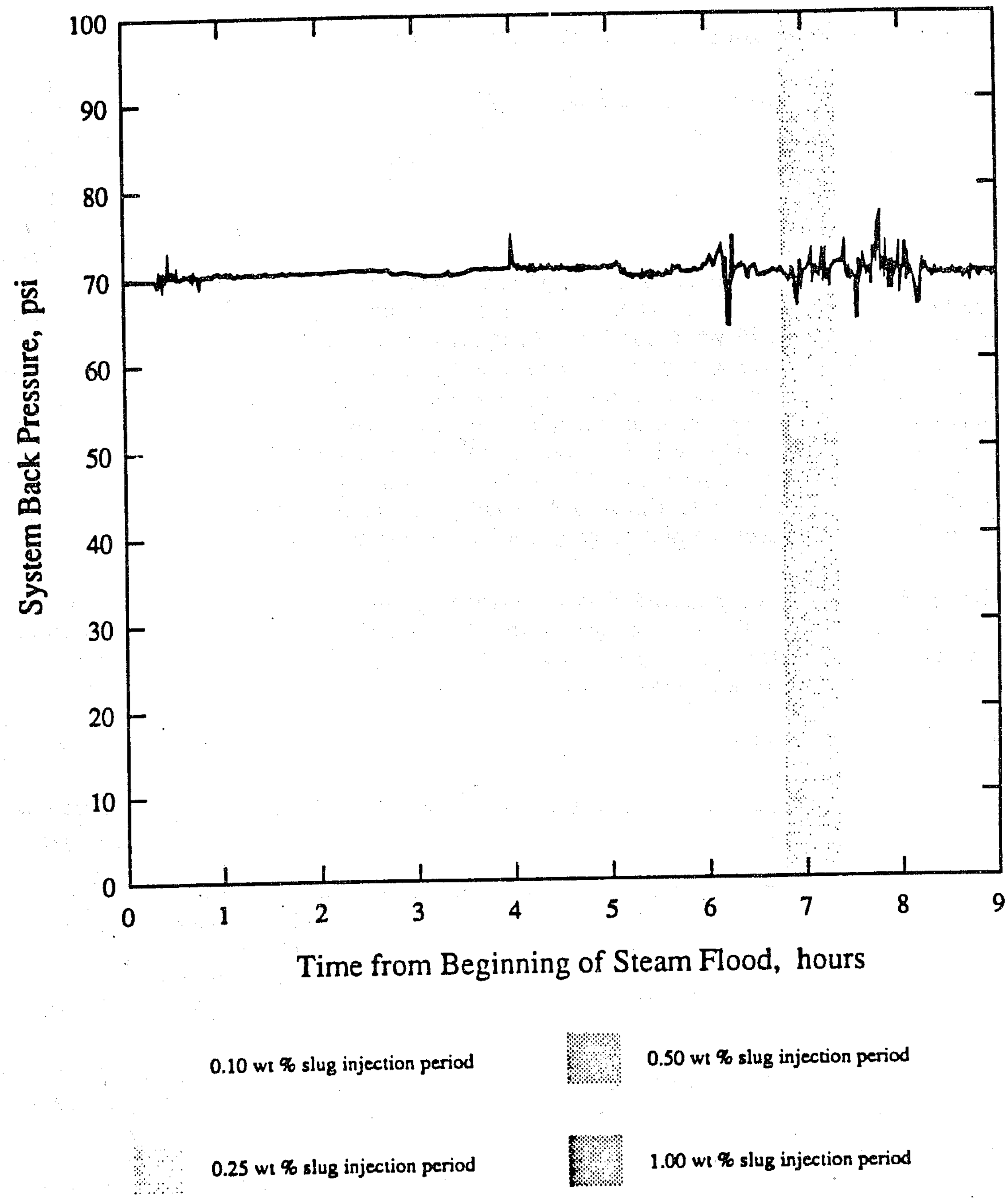

Figure 5.47 : System Back Pressure during Run 22

injection of a 0.25 wt % slug. The injection of the first slug did not result in the generation of foam, but foam was generated by the more concentrated slug. As shown in Figure 5.48, foaming did not occur immediately upon injection of the second slug, but after an interval of 24 minutes had elapsed. A maximum pressure drop across the sandpack of 209 psi was recorded and the pressure response lasted for 83 minutes (Table 5.11).

Figure 5.49 shows that the foam seemed to collapse in the second section at about t = 7.8 hours, before regenerating at about 8.1 hours. The mechanisms by which this occurred are not understood by the authors. Little foam was produced from the system during Run 16, so that it was possible to maintain a relatively stable back pressure (Figure 5.50).

Run 24 began with the injection of a 0.10 wt % slug of the surfactant. As in Run 16, no foaming was observed in response to this first slug. However, foaming was not observed in response to the injection of a 0.25 wt % slug. This is in contrast to the observations of Run 16. Another slug of the 0.25 wt % solution was injected and foaming was observed, but only after a period of 39 minutes had elapsed since injection of the slug had begun (Figure 5.51). It appears that foaming did not occur within the sandpack until after the injection of the third slug was complete. This response time suggests that this surfactant may have been absorbed and then desorbed by the sandpack in a process not fully understood by the authors. A maximum pressure drop across the system of 159 psi was recorded and the response lasted for 76 minutes (Table 5.12). Figure 5.52 shows that foaming was present in all four sandpack sections while Figure 5.53 presents a plot of system back pressure against time.

During Run 24 the computerized data acquisition system failed temporarily resulting in all logged data being lost. The three diagrams and the table relating to this particular experiment were reconstructed from the records produced by the chart recorders connected to the pressure transducers. The data presented is therefore not as accurate as that for other runs.

Shell Enordet LTS 1618D (Run 12)

Run 12 studied Shell's linear toluene sulphonate surfactant, Enordet LTS 1618D. After the injection of 0.10 wt % and 0.25 wt % slugs did not induce foaming within the sandpack, two 0.50 wt % slugs were injected with favourable results. Figure 5.54 shows that the injection of the third slug produced a maximum pressure drop of 42 psi. The foam only began to form after injection of the surfactant slug had stopped. The foam did not collapse completely before the injection of the next slug, but persisted for over three hours with a pressure drop across the system of about 10 psi being maintained. Injection of the last slug yielded a pressure drop of 185 psi and the response lasted for 70 minutes before completely collapsing (Table 5.13).

An examination of the pressure gradient traces presented in Figure 5.55 shows that foaming occurred only in the first two sections of the sandpack in response to the injection of the third slug. Also, it was the foam existing in the second section that was largely responsible for the pressure drop being maintained at an increased level between the third and fourth slugs. Foaming occurred in all four sandpack sections in response to the last slug. The variation in the back pressure of the system is presented in Figure 5.56.

5.3.12. Shell Enordet LTS 18 (Run 23)

Run 23 was performed to study the foam-forming ability of Shell's Enordet LTS 18 surfactant. During the course of this run two slugs of a 0.10 wt % solution were injected with increases in the pressure drop across the system being recorded in response to both slugs. A

Table 5.11 : Summary of Pressure Response Data for Shell Enordet IOS2024 (Run 16)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	--	--
Slug Injection					
Start Time (hr)		5.272	6.976	--	--
Stop Time (hr)		5.862	7.566	--	--
Duration (min)		35.4	35.4	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	44.6	--	--
	Time (hr)	--	7.57	--	--
Section 2	ΔP_2 (psi)	--	48.9	--	--
	Time (hr)	--	7.68	--	--
Section 3	ΔP_3 (psi)	--	90.1	--	--
	Time (hr)	--	8.27	--	--
Section 4	ΔP_4 (psi)	--	104.3	--	--
	Time (hr)	--	8.41	--	--
Entire Tube	ΔP (psi)	--	208.5	--	--
	Time (hr)	--	8.28	--	--
Duration of Pressure Response†					
Section 1	Time (min)	--	81	--	--
Section 2	Time (min)	--	77	--	--
Section 3	Time (min)	--	73	--	--
Section 4	Time (min)	--	77	--	--
Entire Tube	Time (min)	--	83	--	--
Response Time Lag (min)		--	24	--	--

† Duration of pressure response as defined in Section 5.2.

Table 5.12 : Summary of pressure Response Data for Shell Enordet IOS2024 (Run 24)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	0.50	--
Slug Injection					
Start Time (hr)		4.998	6.706	8.415	--
Stop Time (hr)		5.588	7.296	9.006	--
Duration (min)		35.4	35.4	35.4	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	--	39.0	--
	Time (hr)	--	--	9.18	--
Section 2	ΔP_2 (psi)	--	--	53.5	--
	Time (hr)	--	--	9.22	--
Section 3	ΔP_3 (psi)	--	--	69.9	--
	Time (hr)	--	--	9.36	--
Section 4	ΔP_4 (psi)	--	--	92.9	--
	Time (hr)	--	--	9.72	--
Entire Tube	ΔP (psi)	--	--	158.6	--
	Time (hr)	--	--	9.52	--
Duration of Pressure Response†					
Section 1	Time (min)	--	--	17	--
Section 2	Time (min)	--	--	34	--
Section 3	Time (min)	--	--	67	--
Section 4	Time (min)	--	--	62	--
Entire Tube	Time (min)	--	--	76	--
Response Time Lag (min)		--	--	39	--

† Duration of pressure response as defined in Section 5.2.

NOTE Above data reconstructed from chart records.

Table 5.13 : Summary of Pressure Response Data for Shell Enordet LTS1618D (Run 8)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.25	0.50	0.50
Slug Injection					
Start Time (hr)		5.010	6.882	8.964	13.001
Stop Time (hr)		5.606	7.472	9.554	13.591
Duration (min)		35.7	35.4	35.4	35.4
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	--	21.6	28.8
	Time (hr)	--	--	9.86	13.50
Section 2	ΔP_2 (psi)	--	--	19.9	53.5
	Time (hr)	--	--	9.99	13.72
Section 3	ΔP_3 (psi)	--	--	--	67.9
	Time (hr)	--	--	--	13.70
Section 4	ΔP_4 (psi)	--	--	--	82.8
	Time (hr)	--	--	--	14.00
Entire Tube	ΔP (psi)	--	--	42.1	185.3
	Time (hr)	--	--	9.98	13.93
Duration of Pressure Response†					
Section 1	Time (min)	--	--	24	45
Section 2	Time (min)	--	--	> 189 **	50
Section 3	Time (min)	--	--	--	61
Section 4	Time (min)	--	--	--	51
Entire Tube	Time (min)	--	--	> 206 **	70
Response Time Lag (min)		--	--	41	21

† Duration of pressure response as defined in Section 5.2.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

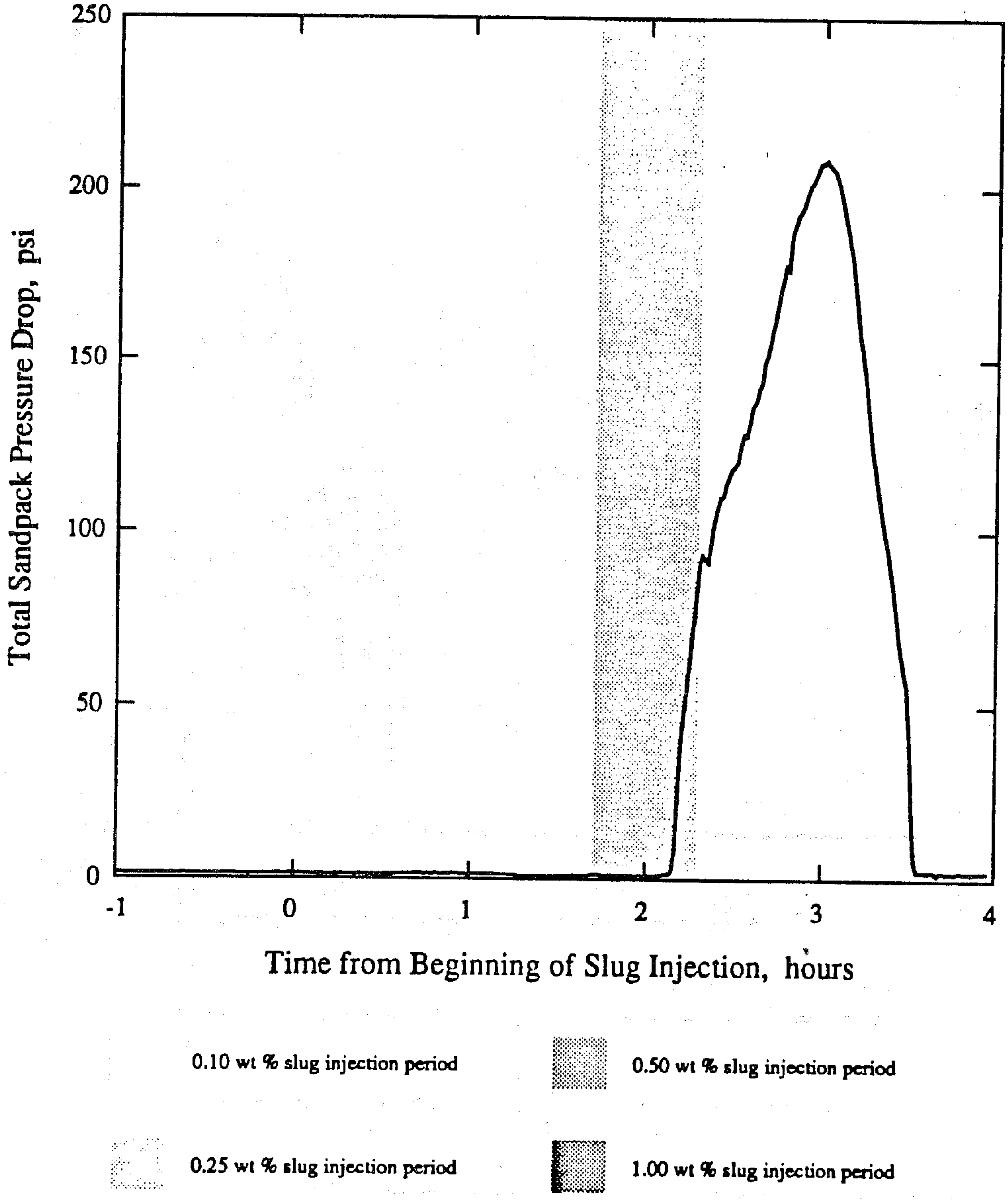

Figure 5.48 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet IOS 2024 - Run 16

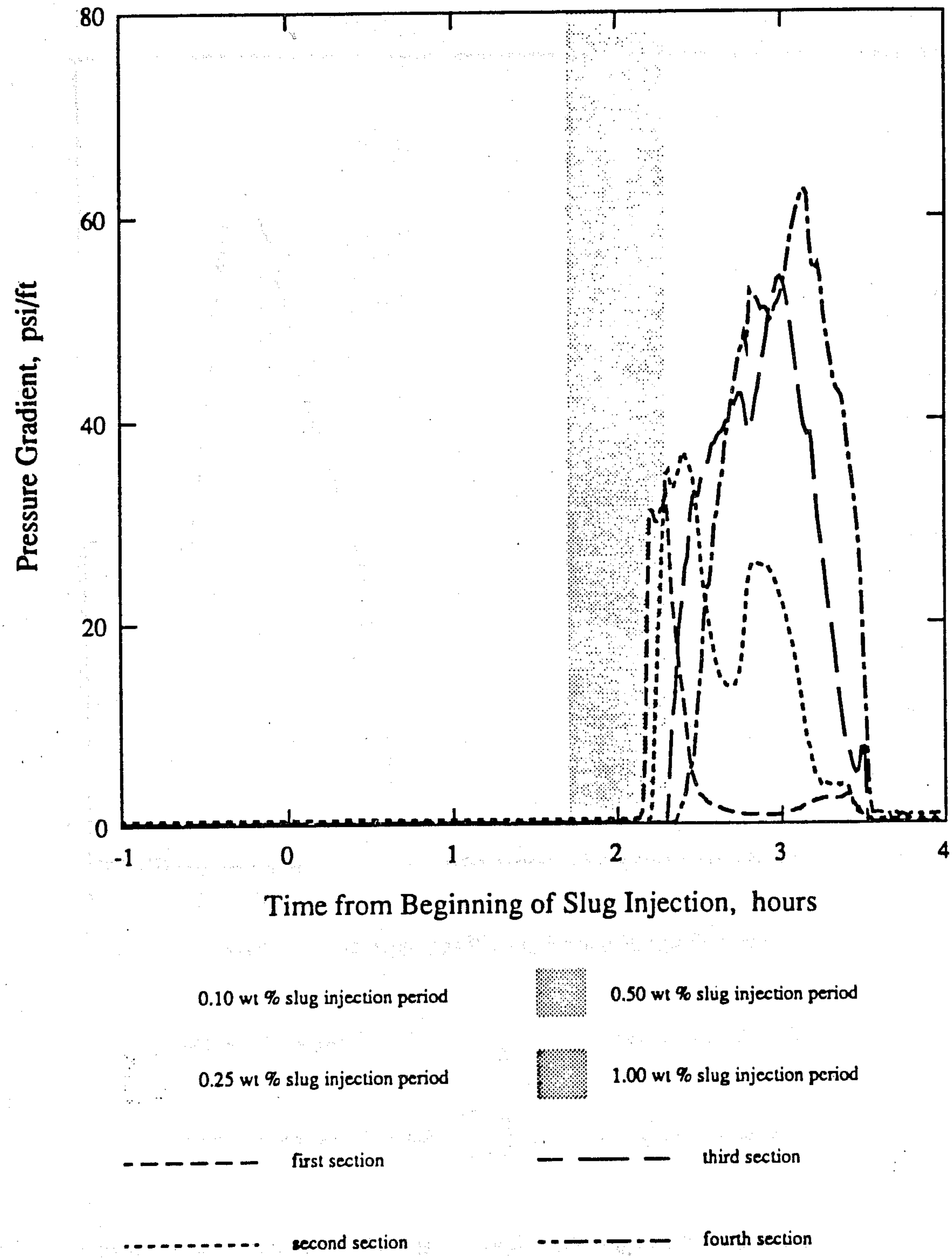

Figure 5.49 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet IOS 2024 - Run 16

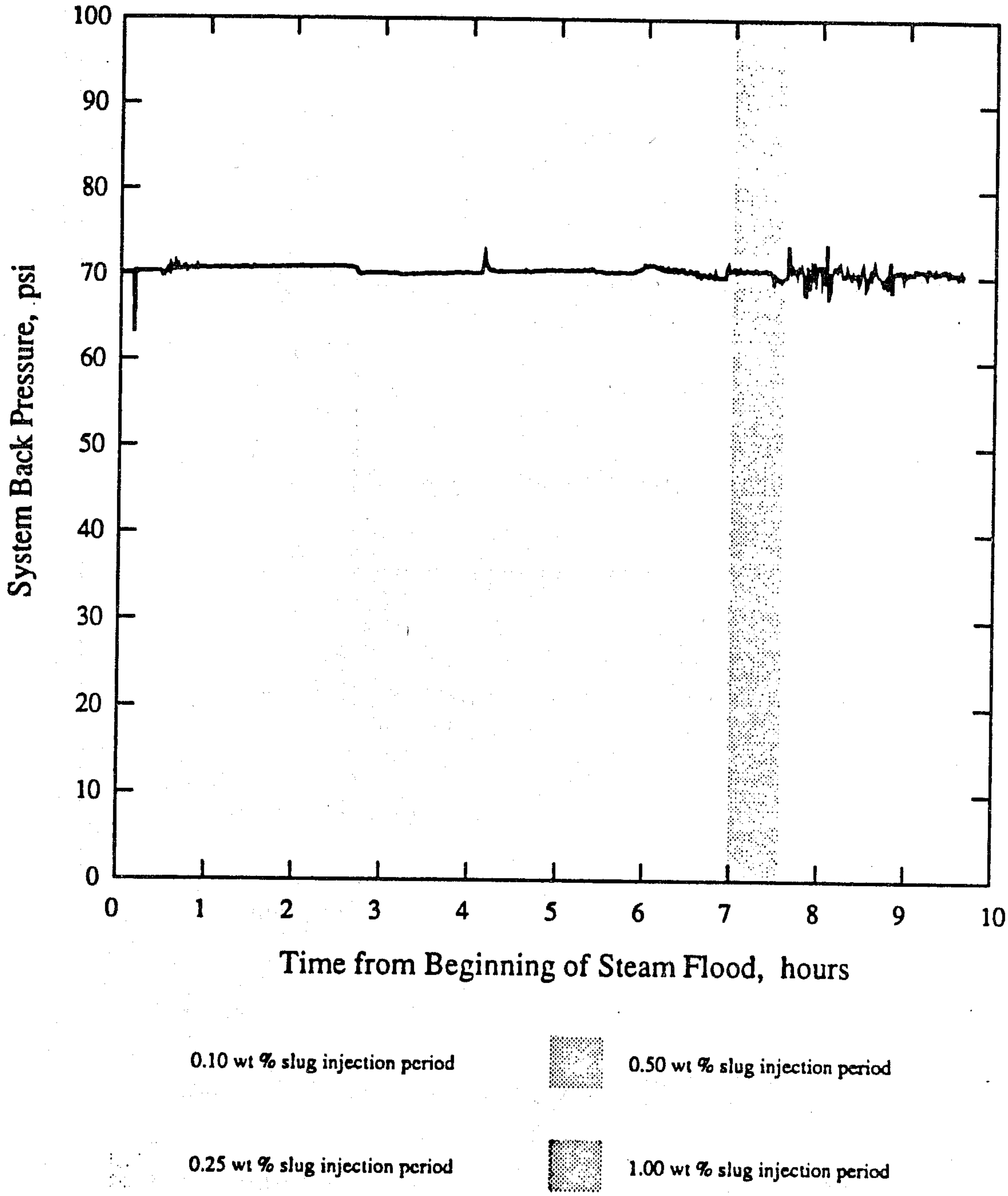

Figure 5.50 : System Back Pressure during Run 16

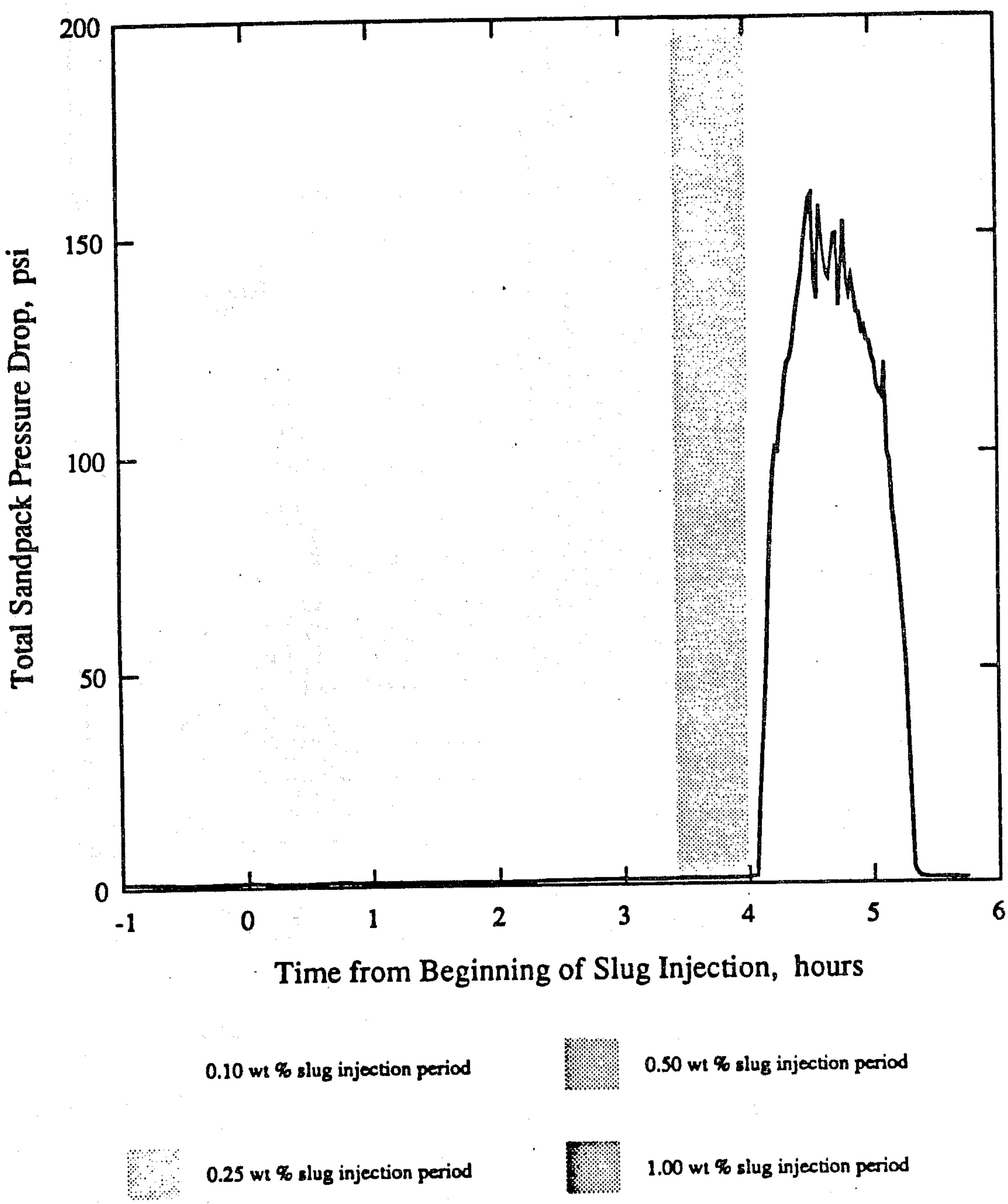

Figure 5.51 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet IOS 2024 - Run 24

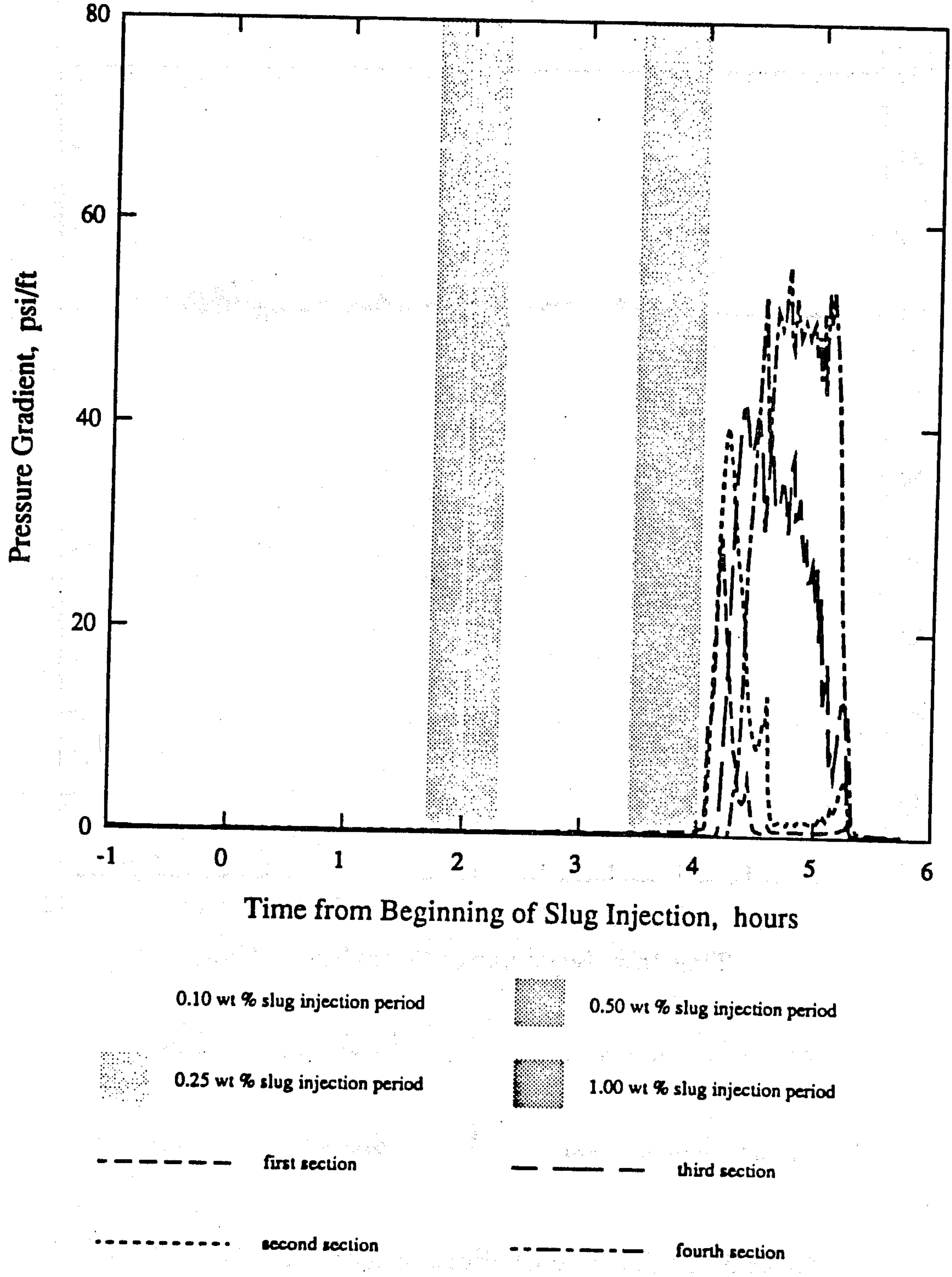

Figure 5.52 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Shell Enordet IOS 2024 - Run 24

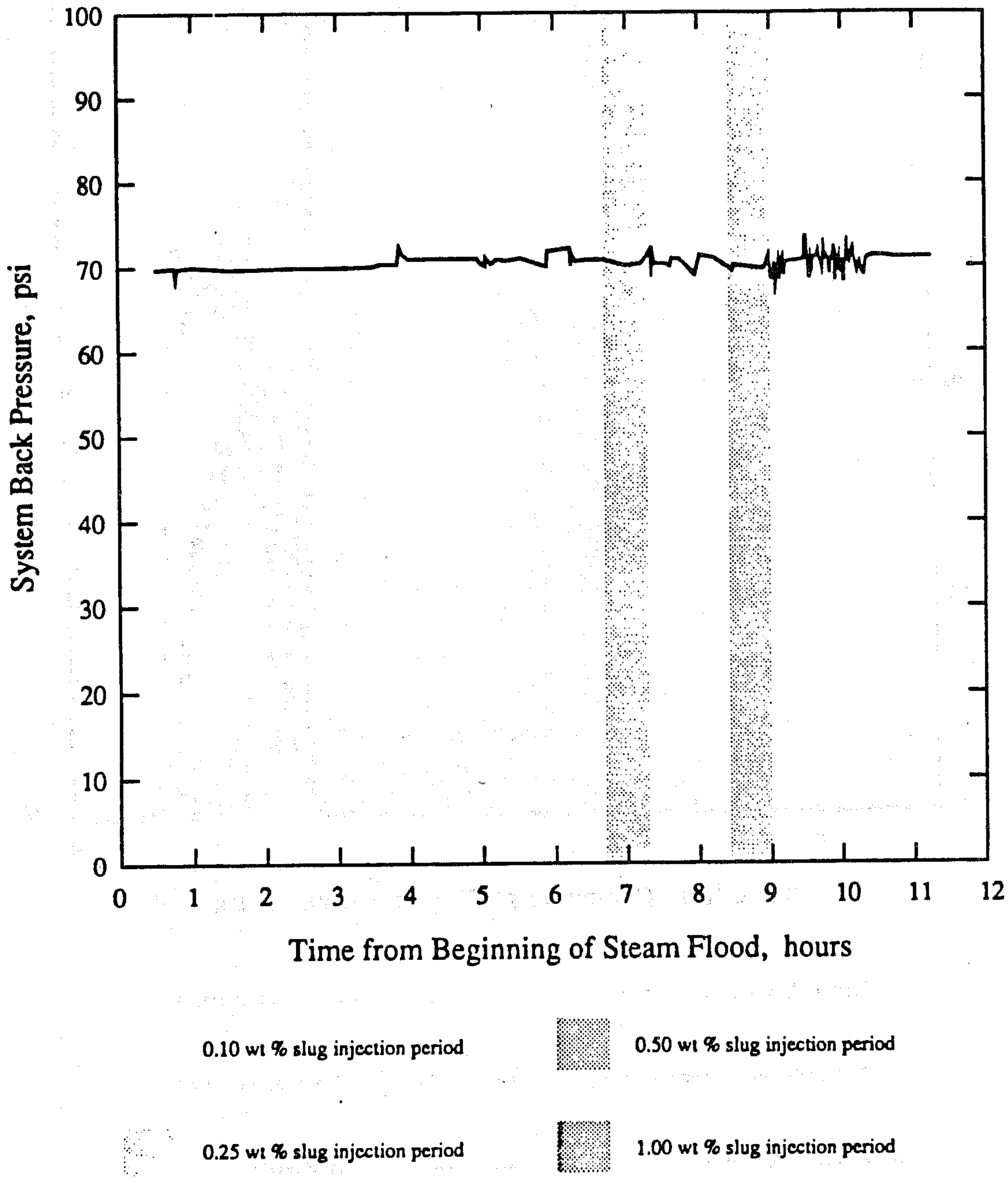

Figure 5.53 : System Back Pressure during Run 24

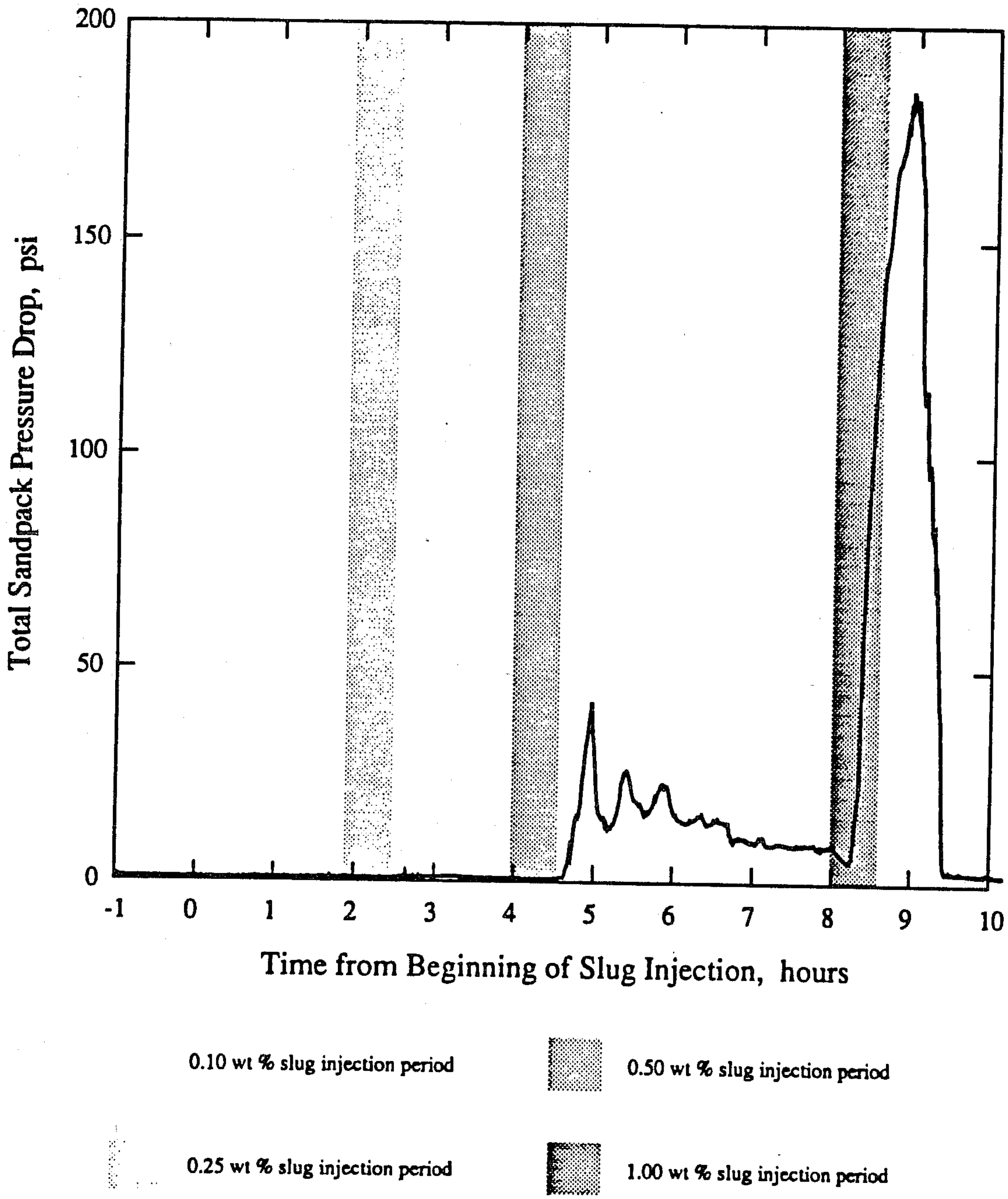

Figure 5.54 : Total Pressure Drop Response to Injection of Four Slugs of Shell Enordet LTS 1618D - Run 12

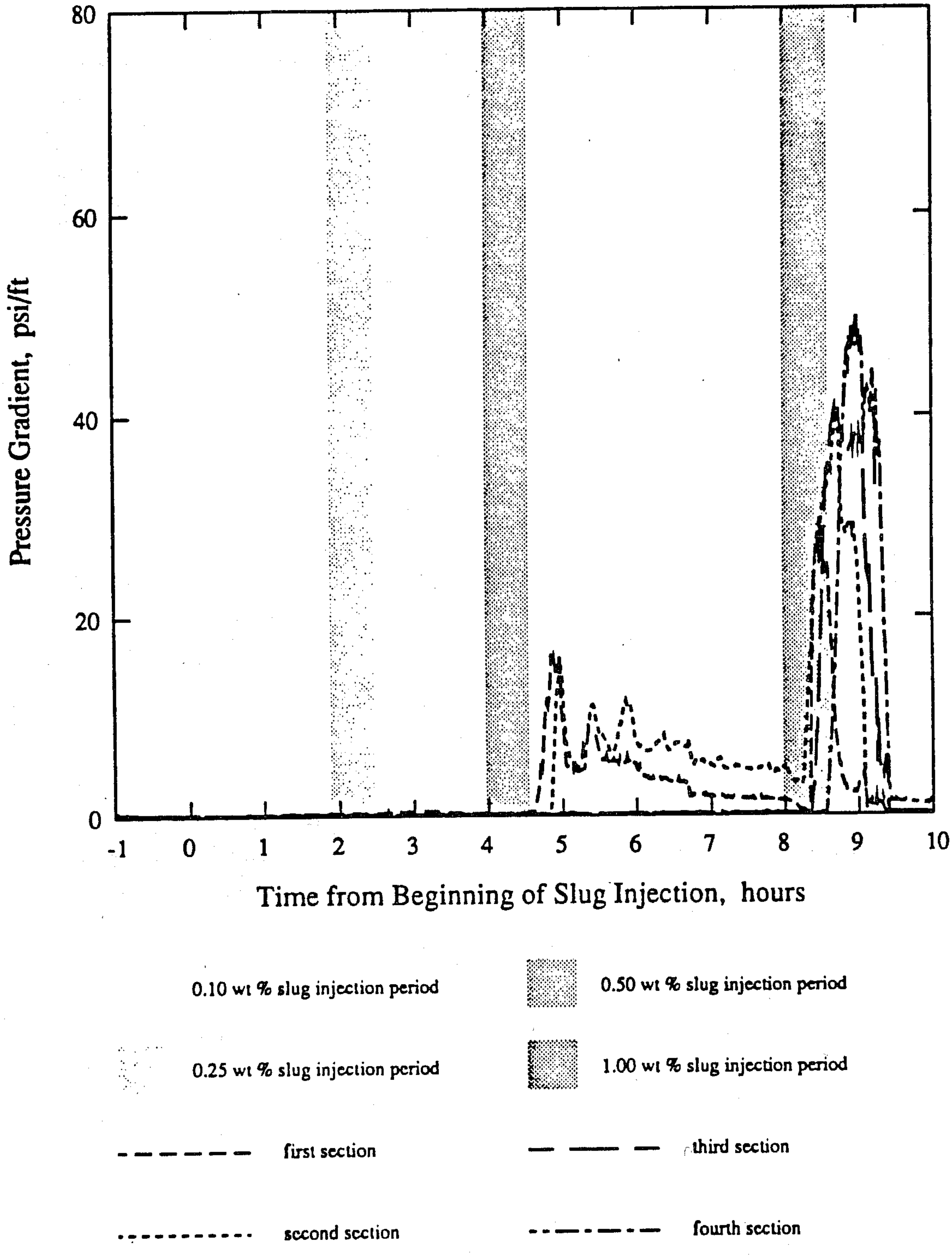

Figure 5.55 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Four Slugs of Shell Enordet LTS 1618D - Run 12

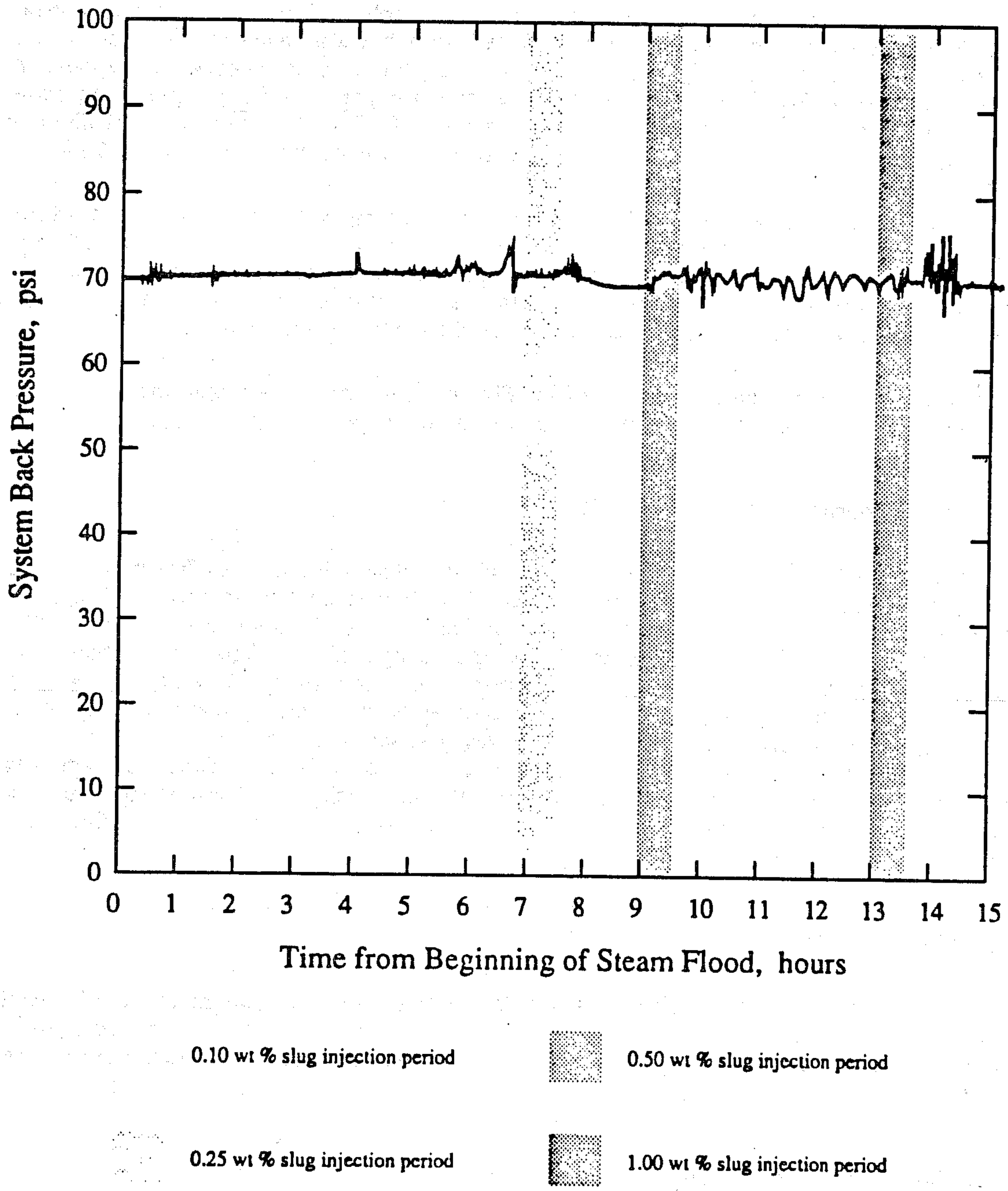

Figure 5.56 : System Back Pressure during Run 19

plot of pressure drop across the sandpack with time for this run is presented in Figure 5.57. The pressure response behaviour displayed in this diagram contains many features similar to those observed for LTS 1618D presented in Figure 5.54. As with LTS 1618D foaming did not occur until after the injection of the surfactant slug was complete. Then, after reaching a maximum, the pressure drop did not decrease back to near-zero, but was maintained at about 14 psi until the injection of the next slug; i.e. the foam persisted for about two hours. In response to injection of the next slug, foaming was more rapid, and stronger, with its collapse being complete. It should be noted however, that LTS 18 foamed at 0.10 wt %, while LTS 1618D only foamed at 0.50 wt %. The pressure response data for Run 23 is summarized in Table 5.14.

The data presented in Figure 5.58 indicates that foaming was present in the first three sections of the sandpack in response to injection of the first slug. As with the LTS 1618D surfactant, it was persistent foam in the second sandpack section that resulted in the sustained high pressure drop across the sandpack between the injection of the two surfactant slugs. Foam was generated in all four sandpack sections by the second slug of Run 23.

The back pressure trace is presented in Figure 5.59, and shows that there were no significant variations in the system back pressure during the experiment.

5.3.13. Shell Enordet LXS 814 (Run 14)

Shell's Enordet LXS814 was the first linear alkyl-xylene sulphonate surfactant tested. as its designation suggests, this preparation consists of molecules containing between 8 and 14 carbon atoms in the alkyl chains. During Run 14, four slugs of 0.10 wt %, 0.25 wt %, 0.50 wt % and finally 1.0 wt % were injected into the sandpack. As Figure 5.60 shows, no significant variations in the overall pressure drop across the sandpack were observed in response to any of the four surfactant slugs. This suggests that foaming was not being spontaneously generated within the sandpack. Foam was observed being produced from the outlet of the back pressure regulator during this experiment, but it is believed that this foam was being generated within the regulator and not within the sandpack. This view is supported by the fact that no foam was observed to pass through the glass observation tube on the outlet line.

5.3.14. Shell Enordet LXS 1112 (Run 28)

Two slugs of a 1.0 wt % solution of Shell's Enordet LXS 1112 surfactant were injected during Run 28. No significant increase in the pressure drop across the system was observed in response to either of the two slugs (Figure 5.61), suggesting that foaming did not occur within the system.

5.3.15. Shell Enordet LXS 1314 (Run 27)

Strong foaming was observed in response to the injection of a single 1.0 wt % slug of Shell's Enordet LXS 1314 surfactant. Figure 5.62 shows that foaming occurred 18 minutes after injection of the surfactant began and persisted for at least two hours (Table 5.15). During this time a maximum pressure drop of 201 psi was observed across the sandpack. Pressure gradient increases were observed in all four sections (Figure 5.63). The diagram also shows that an usual phenomenon occurred during the collapse of the foam at t = 6.5 hours. At this time, foam began to regenerate in the second and third sandpack sections. This resulted in the decrease in the rate of decrease in the pressure drop across the sandpack observed in

Table 5.14 : Summary of Pressure Response Data for Shell Enordet LTS18 (Run 23)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	--	--
Slug Injection					
Start Time (hr)		4.914	7.627	--	--
Stop Time (hr)		5.504	8.219	--	--
Duration (min)		35.4	35.6	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	35.7	42.3	--	--
	Time (hr)	5.55	7.97	--	--
Section 2	ΔP_2 (psi)	37.8	48.3	--	--
	Time (hr)	5.69	8.35	--	--
Section 3	ΔP_3 (psi)	13.4	100.7	--	--
	Time (hr)	5.79	8.73	--	--
Section 4	ΔP_4 (psi)	0.6	103.1	--	--
	Time (hr)	5.88	8.68	--	--
Entire Tube	ΔP (psi)	57.5	236.9	--	--
	Time (hr)	5.68	8.69	--	--
Duration of Pressure Response†					
Section 1	Time (min)	> 120 **	60	--	--
Section 2	Time (min)	> 115 **	54	--	--
Section 3	Time (min)	> 110 **	71	--	--
Section 4	Time (min)	1	61	--	--
Entire Tube	Time (min)	> 120 **	80	--	--
Response Time Lag (min)		31	15	--	--

† Duration of pressure response as defined in Section 5.2.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

Table 5.15 : Summary of Pressure Response Data for Shell Enordet LXS1314 (Run 27)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		1.00	--	--	--
Slug Injection					
Start Time (hr)		5.096	--	--	--
Stop Time (hr)		5.686	--	--	--
Duration (min)		35.4	--	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	39.8	--	--	--
	Time (hr)	5.43	--	--	--
Section 2	ΔP_2 (psi)	53.2	--	--	--
	Time (hr)	5.85	--	--	--
Section 3	ΔP_3 (psi)	81.6	--	--	--
	Time (hr)	6.13	--	--	--
Section 4	ΔP_4 (psi)	114.5	--	--	--
	Time (hr)	6.23	--	--	--
Entire Tube	ΔP (psi)	201.2	--	--	--
	Time (hr)	6.13	--	--	--
Duration of Pressure Response†					
Section 1	Time (min)	31	--	--	--
Section 2	Time (min)	106	--	--	--
Section 3	Time (min)	126	--	--	--
Section 4	Time (min)	> 101 **	--	--	--
Entire Tube	Time (min)	> 126 **	--	--	--
Response Time Lag (min)		18	--	--	--

† Duration of pressure response as defined in Section 5.2.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

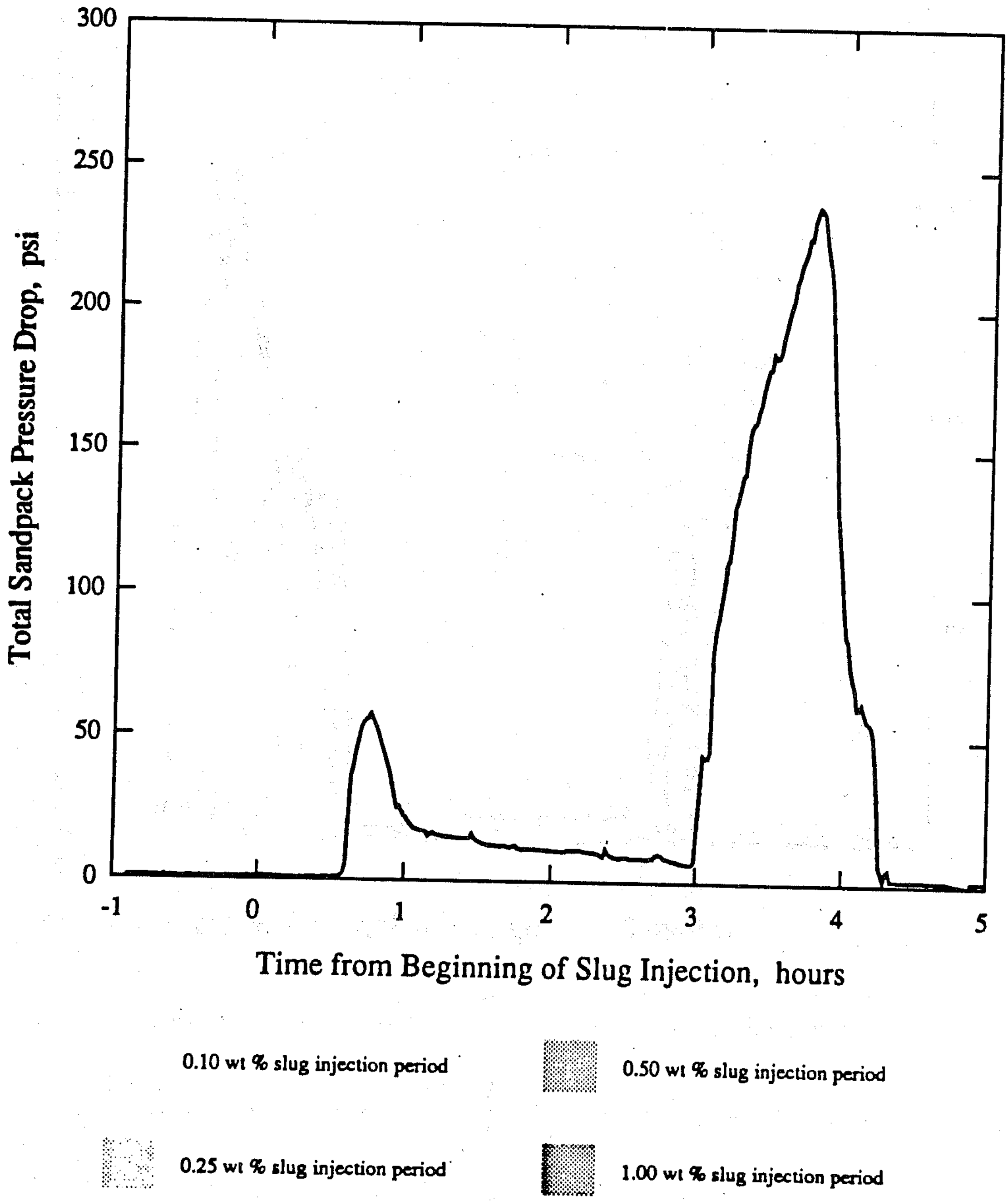

Figure 5.57 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet LTS 18 - Run 23

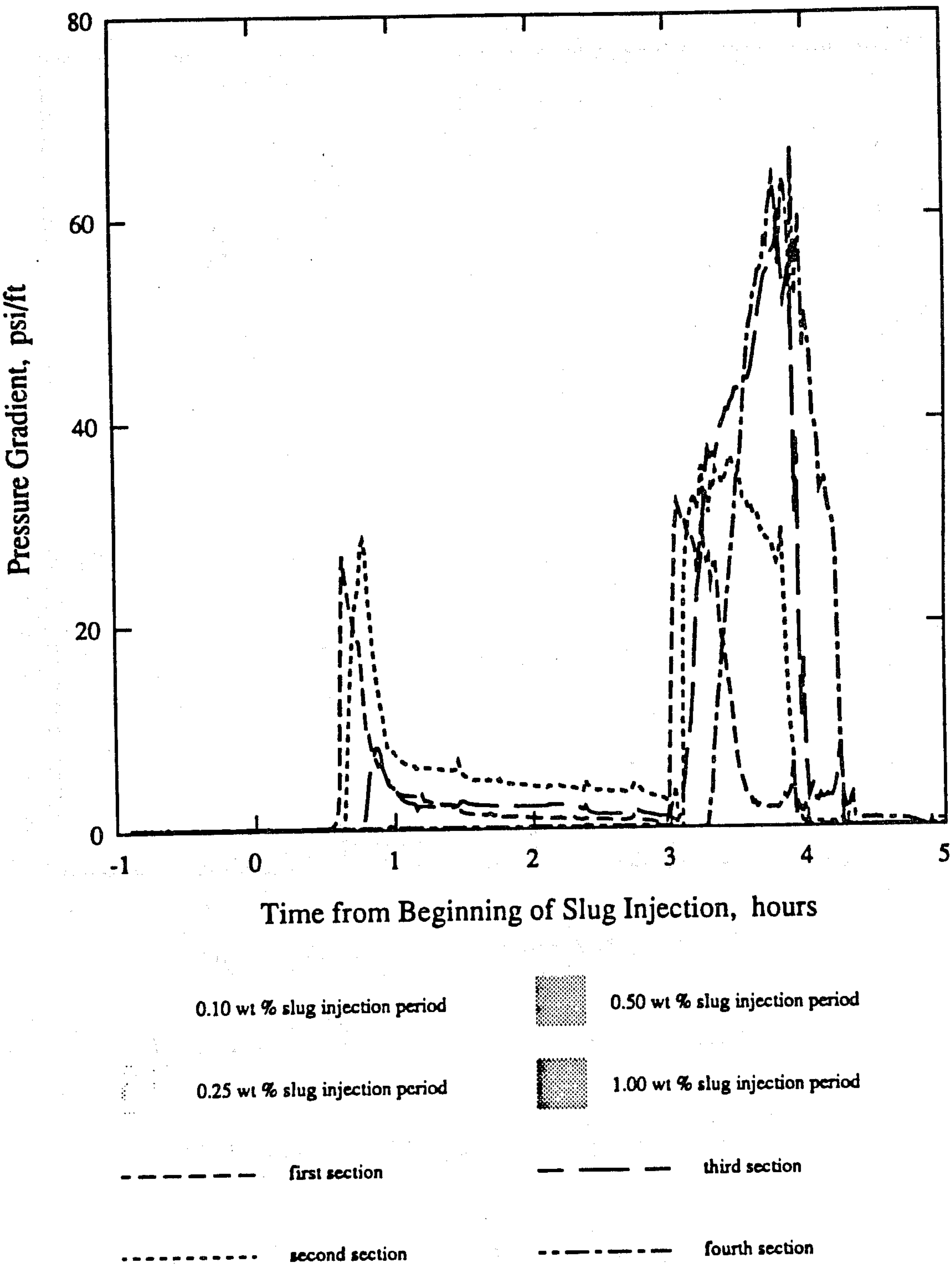

Figure 5.58 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet LTS 18 - Run 23

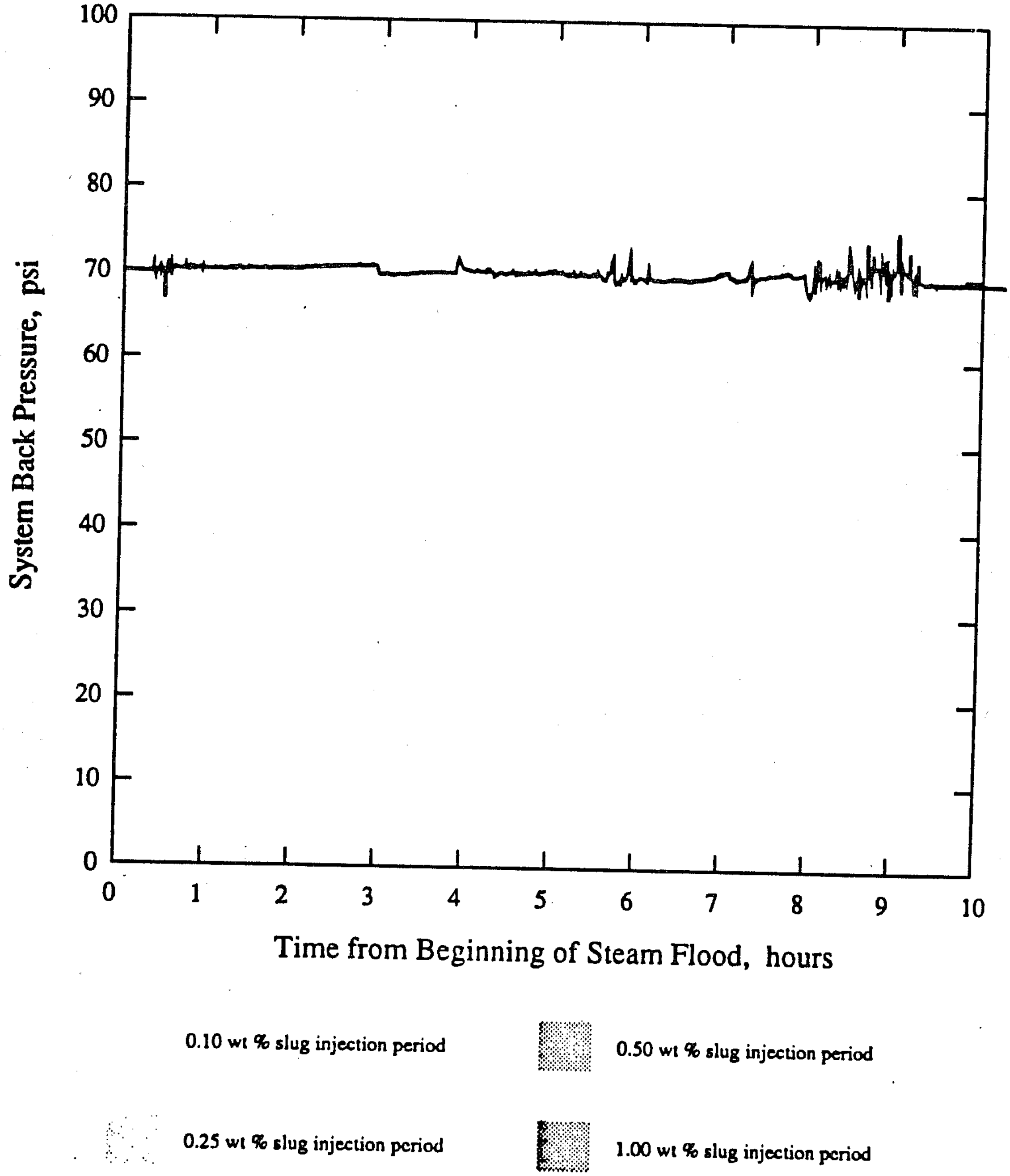

Figure 5.59 : System Back Pressure during Run 19

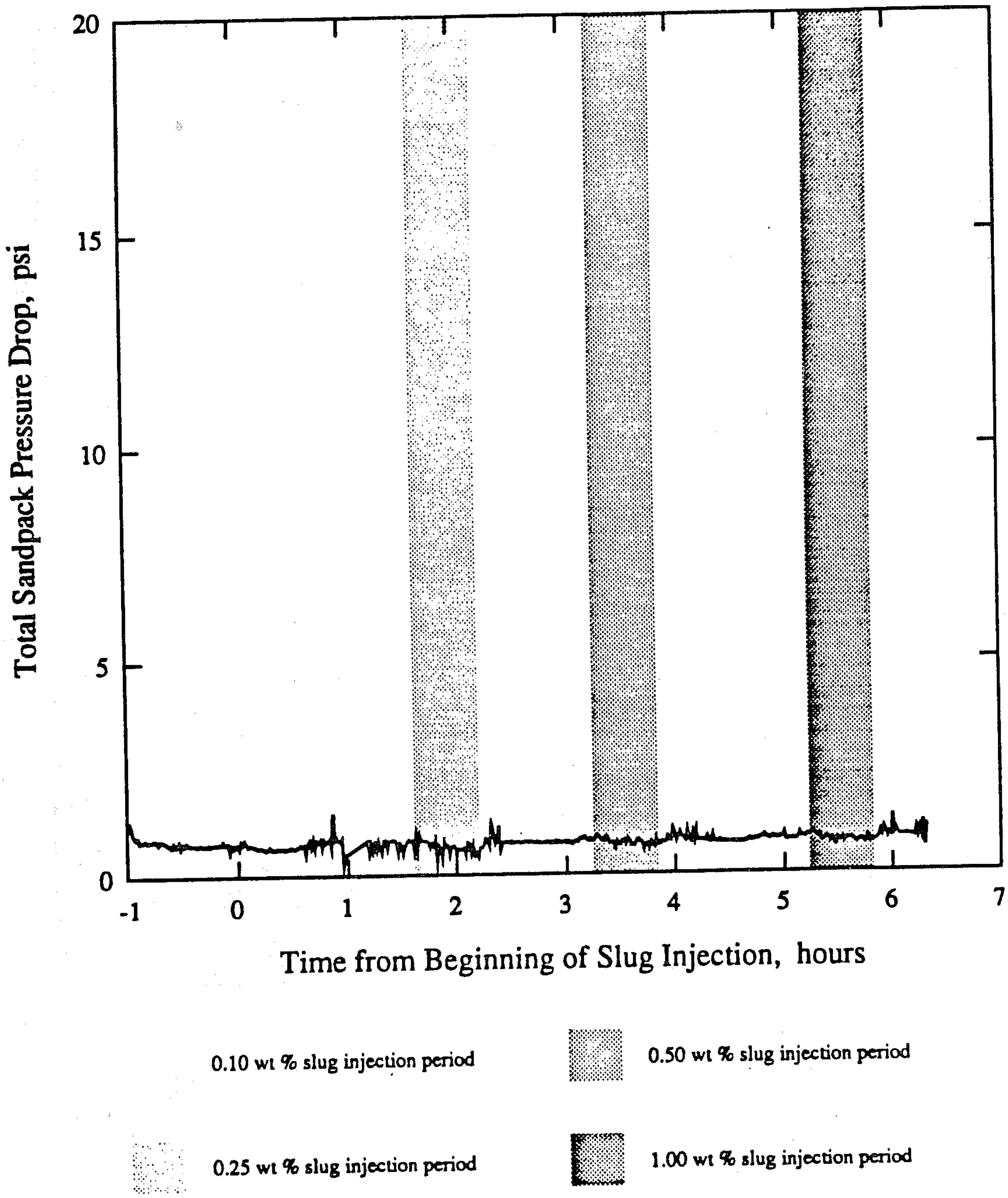

Figure 5.60 : Total Pressure Drop Response to Injection of Four Slugs of Shell Enordet LXS 814 - Run 14

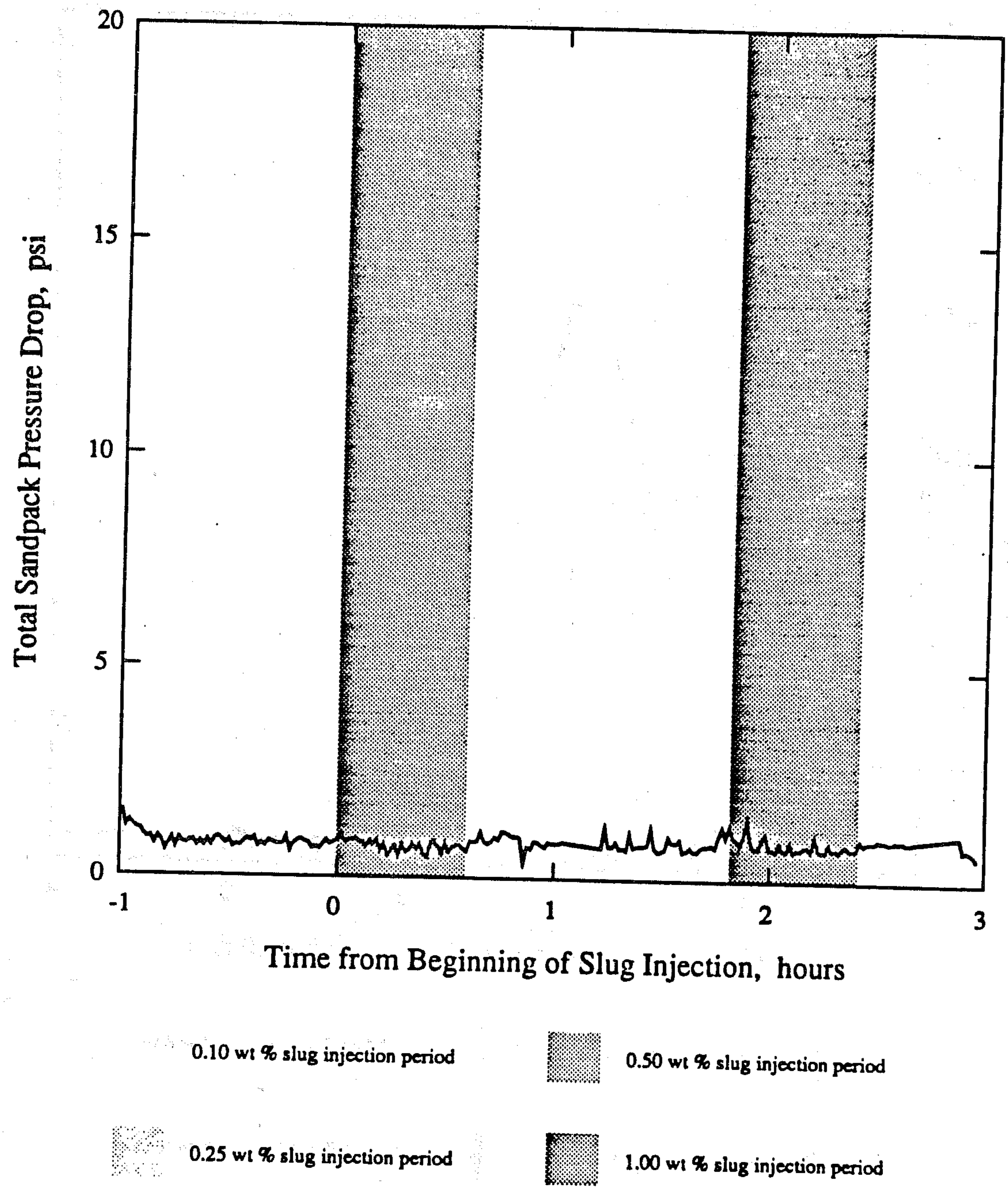

Figure 5.61 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet LXS 1112 - Run 28

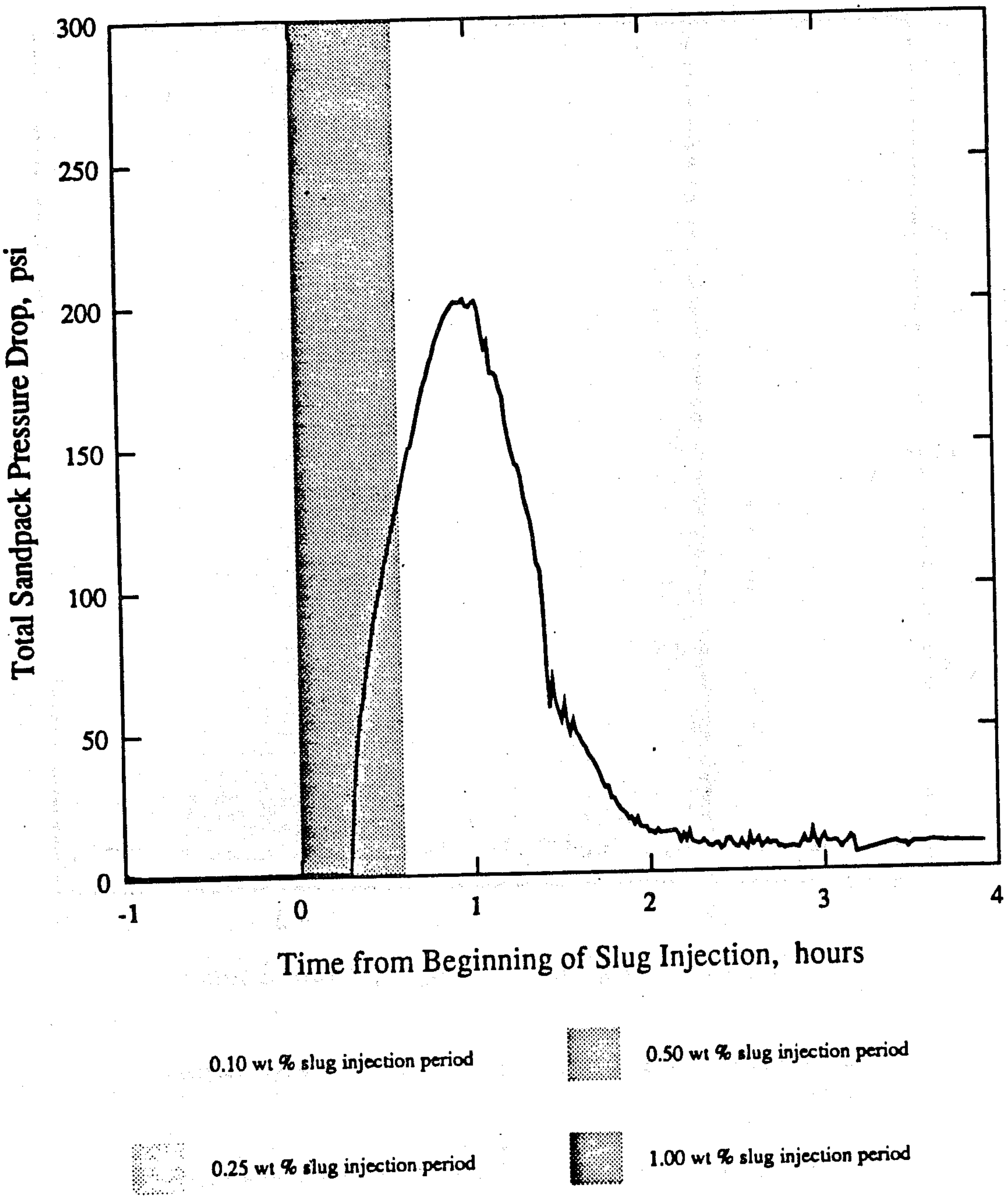

Figure 5.62 : Total Pressure Drop Response to Injection of One Slug of Shell Enordet LXS 1314 - Run 27

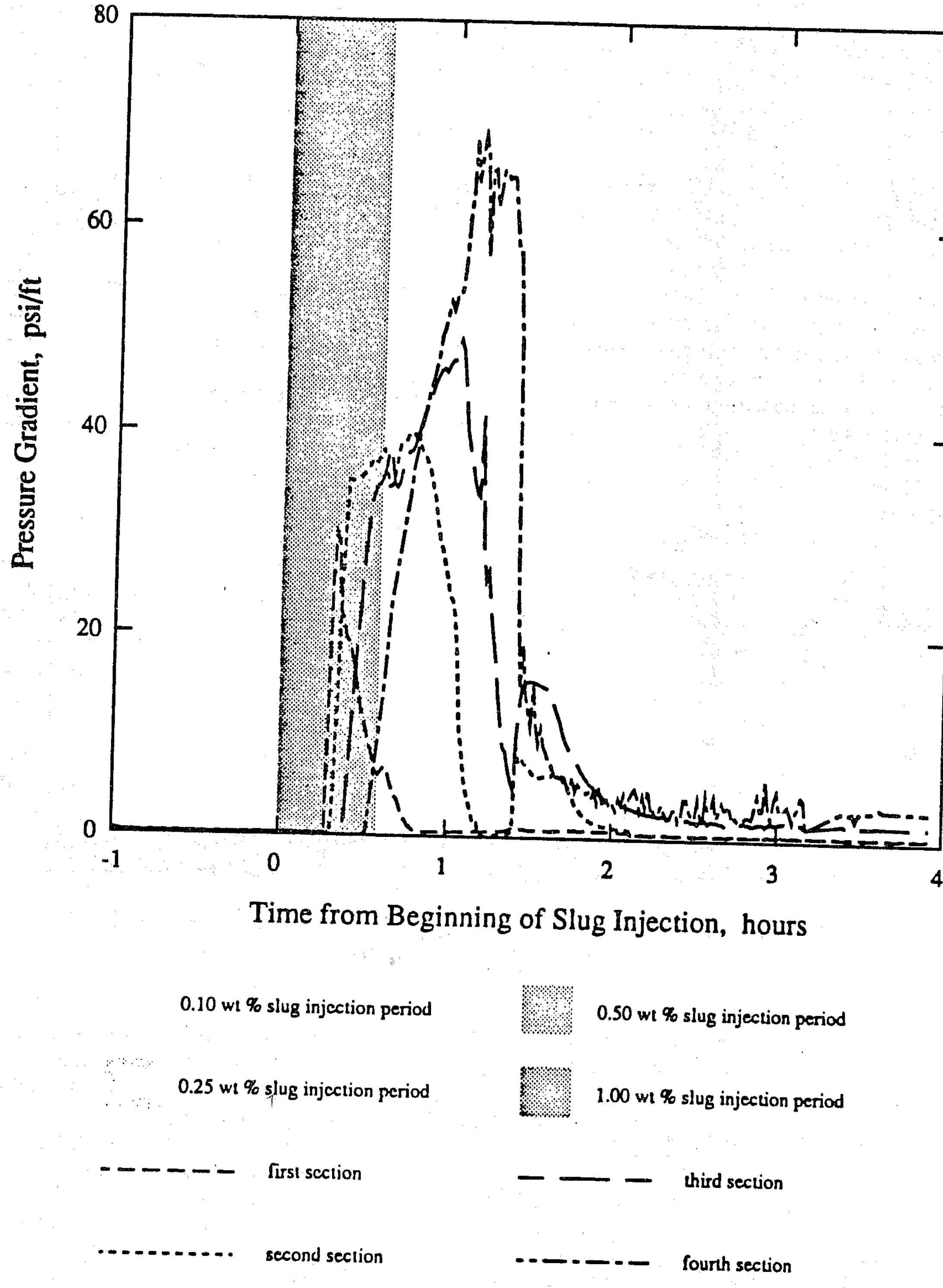

Figure 5.63 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of One Slug of Shell Enordet LXS 1314 - Run 27

Figure 5.62 at t = 6.5 hours. There was no corresponding fluctuation in the system back pressure at this time (Figure 5.64) that could have induced this foaming. The mechanism by which this regeneration occurred is not understood by the authors.

5.3.16. Shell Enordet LXS 16 (Runs 20 and 26)

Two experiments were performed to study the foam-forming ability of Shells' Enordet LXS 16. In the first of these, Run 20, two slugs of a 1.0 wt % solution were injected into the sandpack. After injection of the first slug, which did not produce an increase in the sandpack pressure drop, the filter on the surfactant injection line was found to be blocked. A comparison of the liquid level in the surfactant reservoir before and after injection of the first slug indicated that only a very small amount of the surfactant solution had been injected. The filter was replaced and another slug was injected into the sandpack. This time a drop in the surfactant reservoir level indicated that the solution was being successfully injected. In response to this slug, the total pressure drop across the sandpack increased to at least 254 psi (Figure 5.65). aggressive foaming in the fourth sandpack section section caused the pressure transducer in that section to overrange (Figure 5.66). The pressure response data for this run is summarized in Table 5.16, while Figure 5.67 presents a plot of system back pressure versus time for the experiment.

The experiment was repeated in Run 26 in which foaming was observed with the injection of a single slug of a 1.0 wt % solution of the surfactant. Eleven minutes after slug injection was begun the pressure within the system began to increase (Figure 5.68). A maximum pressure drop of 230 psi was observed across the sandpack (Table 5.17) with foaming occurring in all of its four sections (Figure 5.69). The variation is the system back pressure throughout the experiment is shown in Figure 5.70.

The foam generated during Run 26 did not produce a pressure drop as great as that observed in Run 20 (cf 230 psi for Run 26 to 254 psi for Run 20). This may be because the slug that generated the foam in Run 20 was preceded by another, albeit smaller slug, whereas the sole slug injected into the sandpack during Run 26, was injected into a clean sandpack containing no traces of surfactant. Thus, the surfactant concentration in the sandpack during Run 20 may have been slightly higher than during Run 26.

5.3.17. Shell Enordet LXS 18 (Run 17)

The alkyl-xylene sulphonate surfactant with the longest alkyl chains tested was Shells' Enordet LXS 18. Run 17 began with the injection of a 0.25 wt % slug. The customary first slug of 0.10 wt % was not injected because earlier results suggested that this surfactant would not foam at such a low concentration. The 0.25 wt % slug was followed by the injection of a 0.50 wt % slug, but it was not until after the injection of a 1.00 wt % slug that foaming was observed as evidenced by the increase in the pressure drop across the sandpack (Figure 5.71). As with the long-chained IOS 2024, a considerable time passed before foaming began. In fact, all four sandpack section pressure transducers were being calibrated when foaming began within the sandpack. The transducers were quickly switched back on-line but by that time the first two minutes of foaming activity were not recorded. This is noted in Table 5.18. Despite the long time lag of at least 66 minutes, a strong foam was generated within all four sections of the sandpack (Figure 5.72). Figure 5.73 shows that some difficulty was encountered in controlling the system back pressure during the run.

Table 5.16 : Summary of Pressure Response Data for Shell Enordet LXS16 (Run 20)

			Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)			1.00	1.00	--	--
Slug Injection						
	Start Time (hr)		6.006	7.606	--	--
	Stop Time (hr)		6.596	8.196	--	--
	Duration (min)		35.4	35.4	--	--
Maximum Observed Pressure Drop						
	Section 1	ΔP_1 (psi)	--	41.9	--	--
		Time (hr)	--	8.01	--	--
	Section 2	ΔP_2 (psi)	--	69.7	--	--
		Time (hr)	--	8.34	--	--
	Section 3	ΔP_3 (psi)	--	97.1	--	--
		Time (hr)	--	8.84	--	--
	Section 4	ΔP_4 (psi)	--	> 130 ‡	--	--
		Time (hr)	--	? ‡	--	--
	Entire Tube	ΔP (psi)	--	254 ‡	--	--
		Time (hr)	--5.86 ‡	--	--	
Duration of Pressure Response†						
	Section 1	Time (min)	--	74	--	--
	Section 2	Time (min)	--	71	--	--
	Section 3	Time (min)	--	67	--	--
	Section 4	Time (min)	--	59	--	--
	Entire Tube	Time (min)	--	76	--	--
Response Time Lag (min)			--	19	--	--

† Duration of pressure response as defined in Section 5.2.

‡ Transducers overranged during slug injection.

Table 5.17 : Summary of Pressure Response Data for Shell Enordet LXS16 (Run 26)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		1.00	--	--	--
Slug Injection					
Start Time (hr)		5.084	--	--	--
Stop Time (hr)		5.675	--	--	--
Duration (min)		35.4	--	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	46.0	--	--	--
	Time (hr)	5.37	--	--	--
Section 2	ΔP_2 (psi)	58.4	--	--	--
	Time (hr)	5.94	--	--	--
Section 3	ΔP_3 (psi)	114.3	--	--	--
	Time (hr)	6.28	--	--	--
Section 4	ΔP_4 (psi)	123.3	--	--	--
	Time (hr)	6.50	--	--	--
Entire Tube	ΔP (psi)	229.6	--	--	--
	Time (hr)	6.25	--	--	--
Duration of Pressure Response†					
Section 1	Time (min)	82	--	--	--
Section 2	Time (min)	80	--	--	--
Section 3	Time (min)	80	--	--	--
Section 4	Time (min)	70	--	--	--
Entire Tube	Time (min)	87	--	--	--
Response Time Lag (min)		11	--	--	--

† Duration of pressure response as defined in Section 5.2.

Table 5.18 : Summary of Pressure Response Data for Shell Enordet LXS18 (Run 17)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.25	0.50	1.00	--
Slug Injection					
Start Time (hr)		4.981	6.704	8.309	--
Stop Time (hr)		5.571	7.295	8.899	--
Duration (min)		35.4	35.4	35.4	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	--	--	37.3	--
	Time (hr)	--	--	9.49	--
Section 2	ΔP_2 (psi)	--	--	63.3	--
	Time (hr)	--	--	9.56	--
Section 3	ΔP_3 (psi)	--	--	113.0	--
	Time (hr)	--	--	10.38	--
Section 4	ΔP_4 (psi)	--	--	104.9	--
	Time (hr)	--	--	10.18	--
Entire Tube	ΔP (psi)	--	--	246.1	--
	Time (hr)	--	--	10.20	--
Duration of Pressure Response†					
Section 1	Time (min)	--	--	41 [a]	--
Section 2	Time (min)	--	--	82 [a]	--
Section 3	Time (min)	--	--	79 [a]	--
Section 4	Time (min)	--	--	70	--
Entire Tube	Time (min)	--	--	85 [a]	--
Response Time Lag (min)		--	--	66 [a]	--

† Duration of pressure response as defined in Section 5.2.

a Pressure response data during period 9.26hr < t < 9.41hr was lost while transducers were being calibrated. Consequently, the indicated values are minimums only.

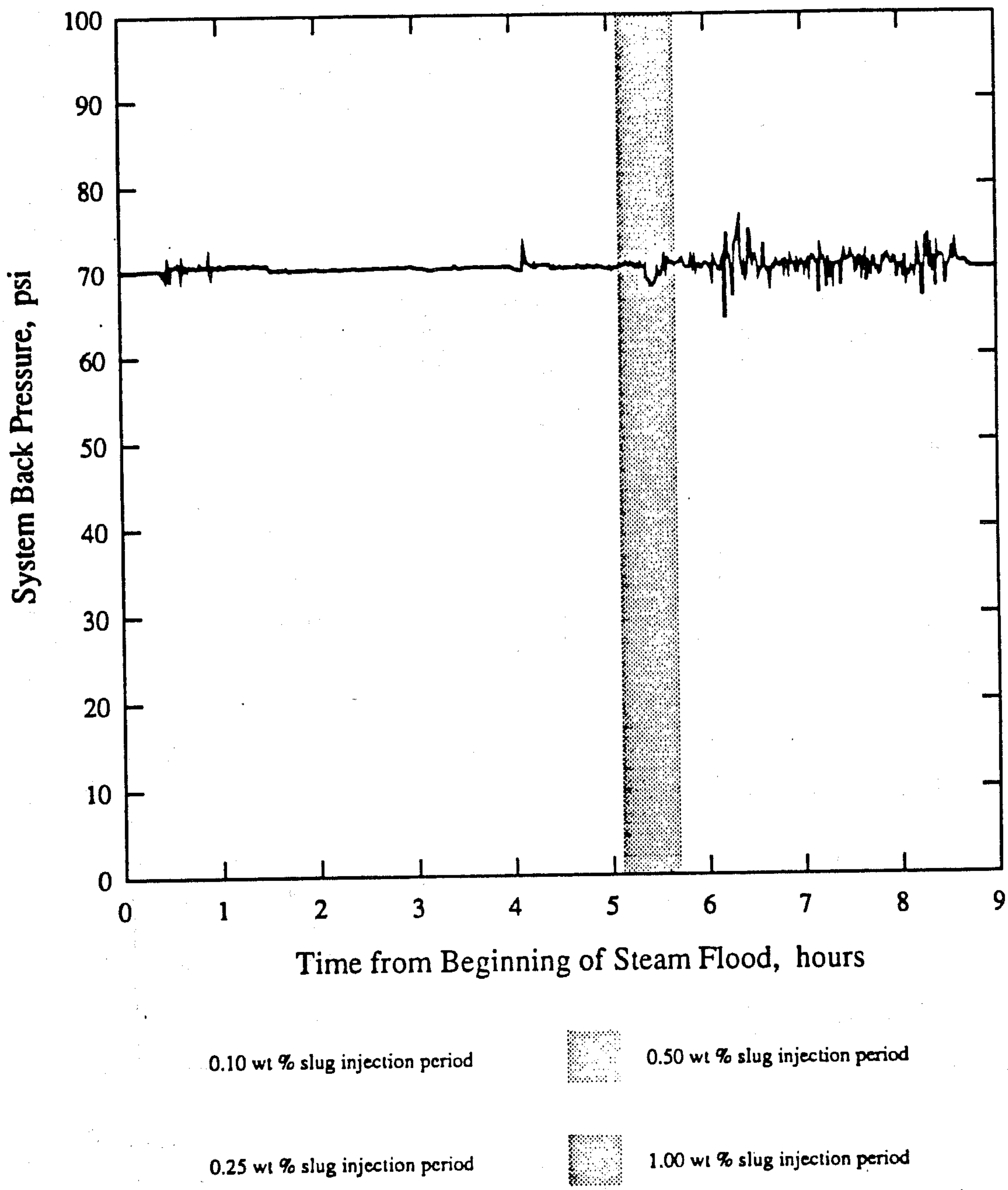

Figure 5.64 : System Back Pressure during Run 27

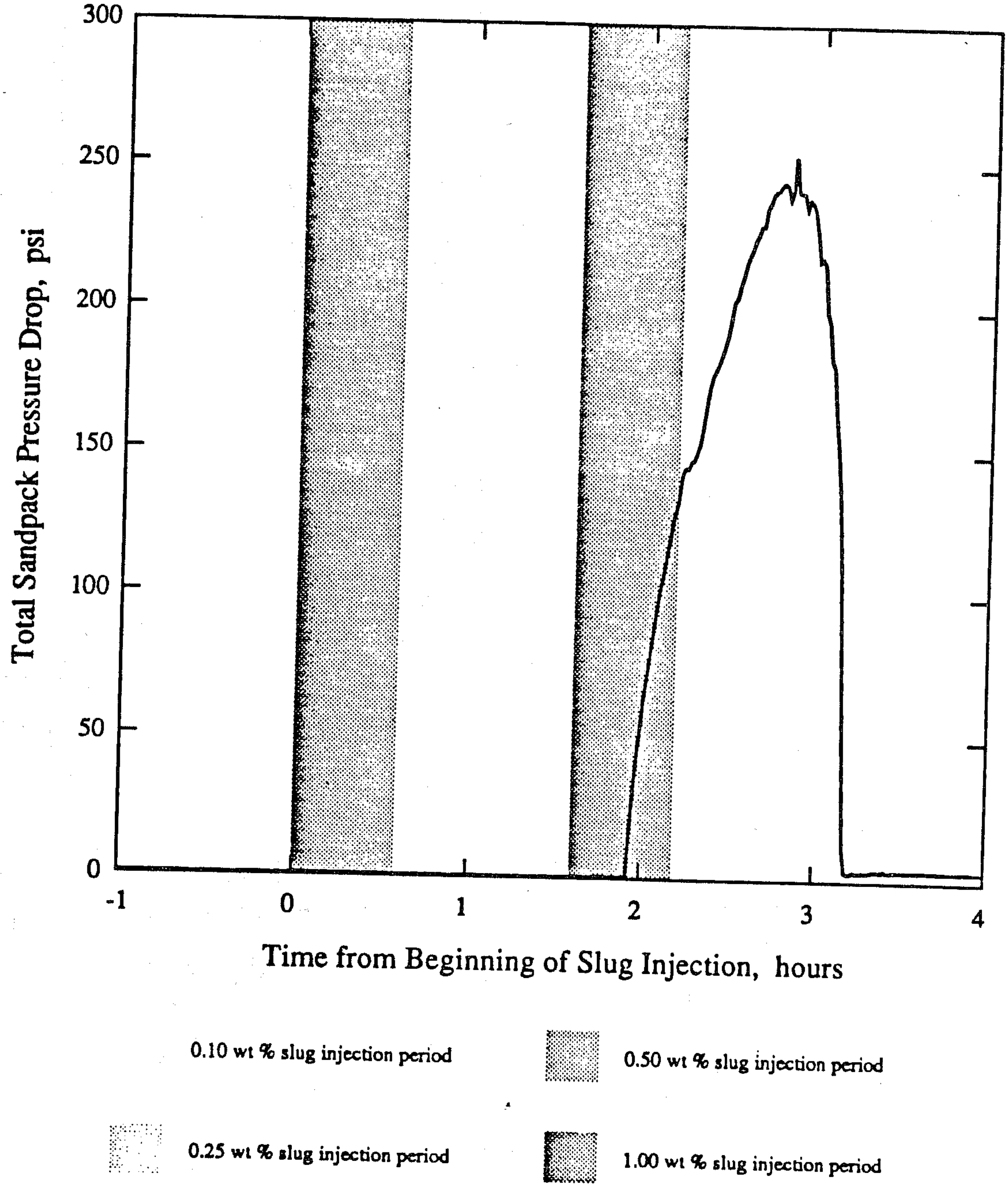

Figure 5.65 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet LXS 16 - Run 20

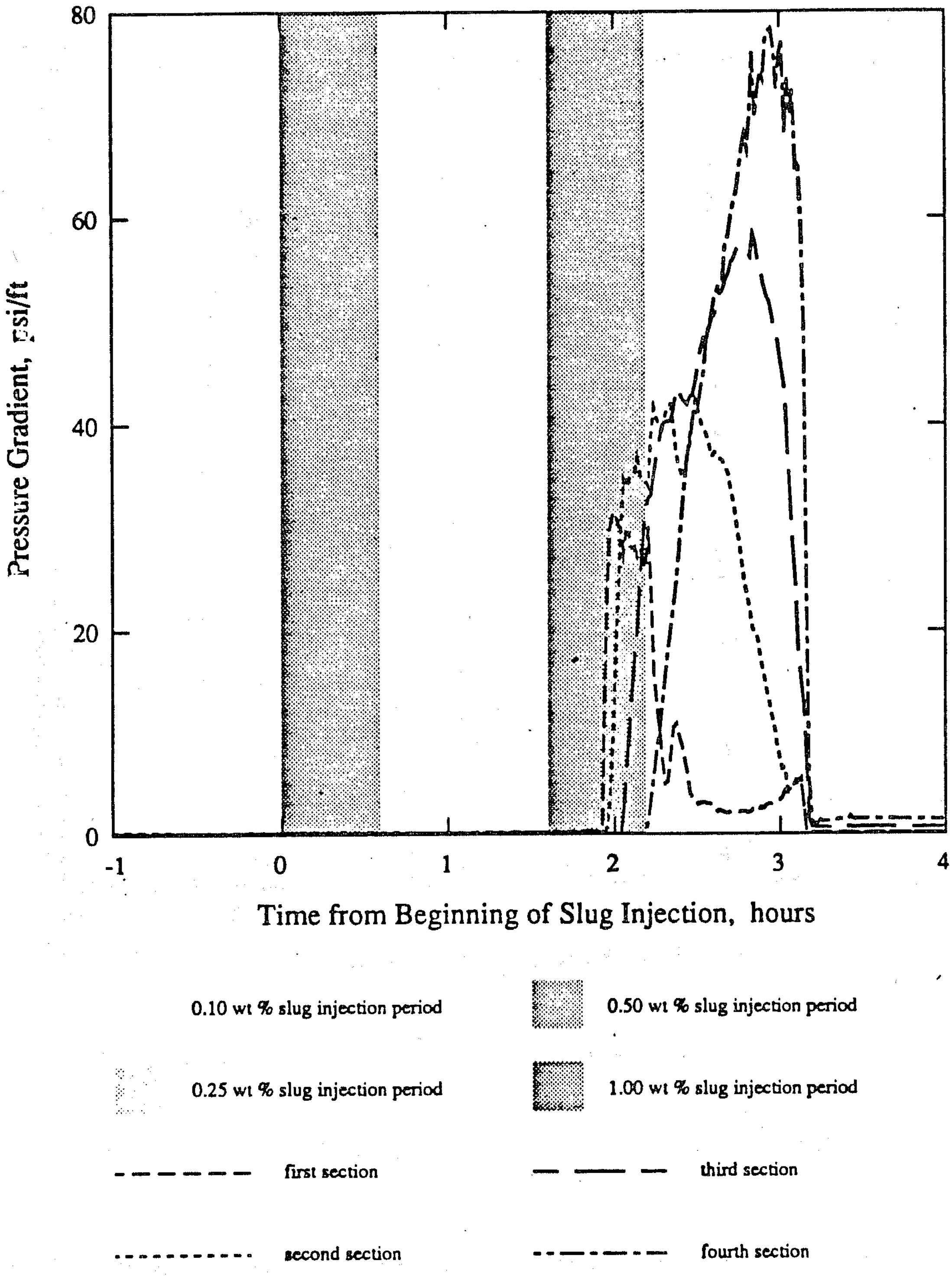

Figure 5.66 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet LXS 16 - Run 20

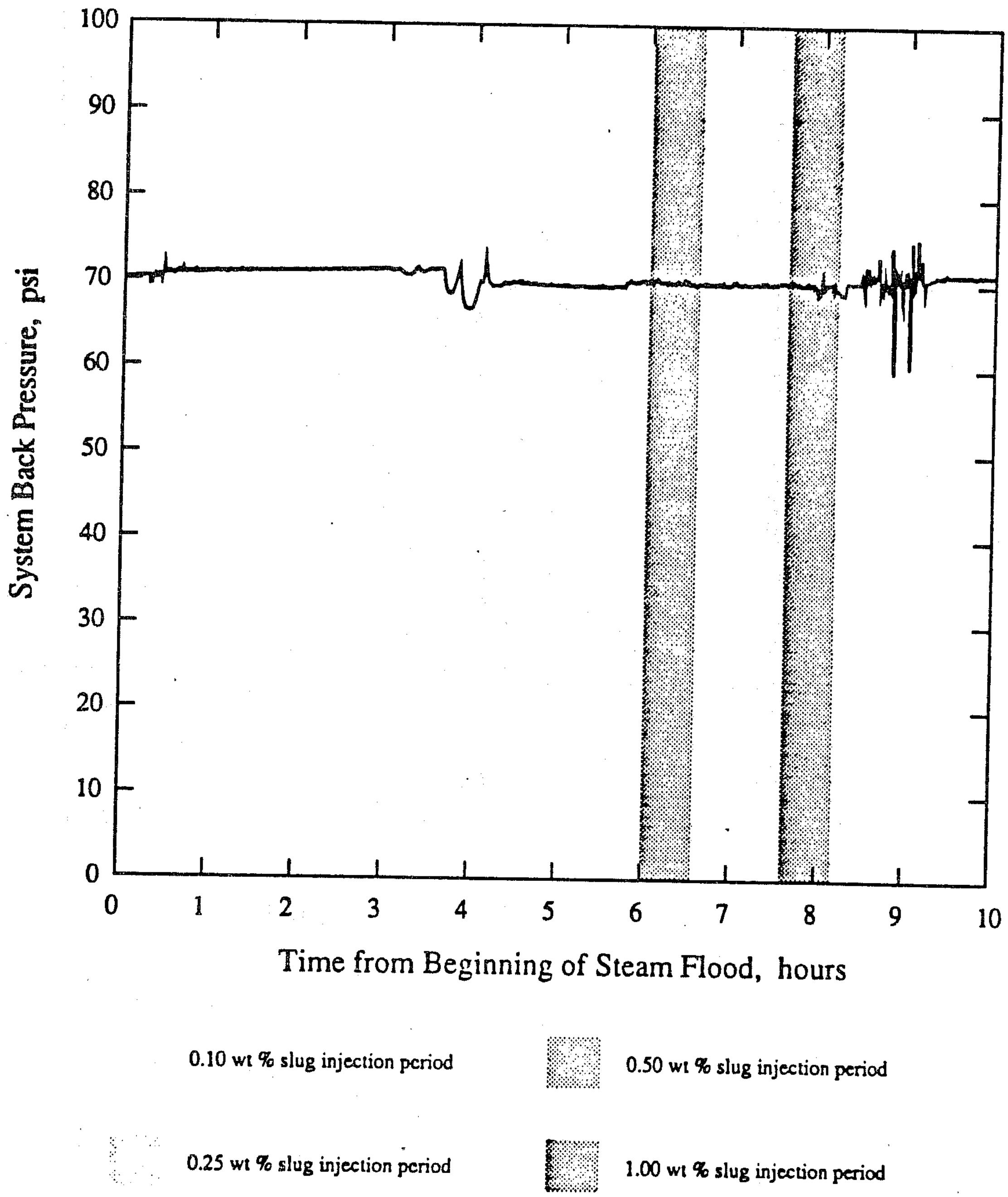

Figure 5.67 : System Back Pressure during Run 20

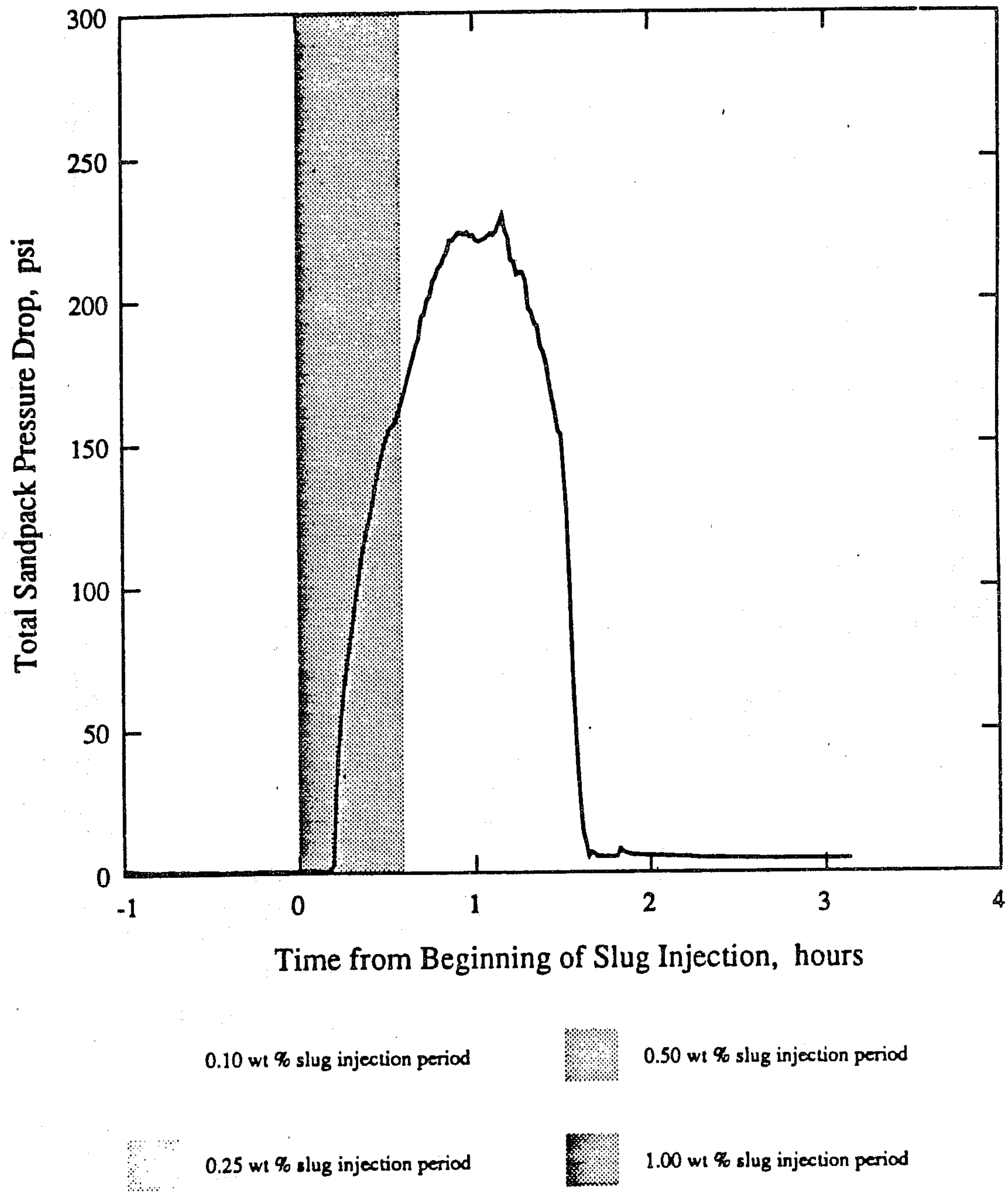

Figure 5.68 : Total Pressure Drop Response to Injection of One Slug of Shell Enordet LXS 16 - Run 26

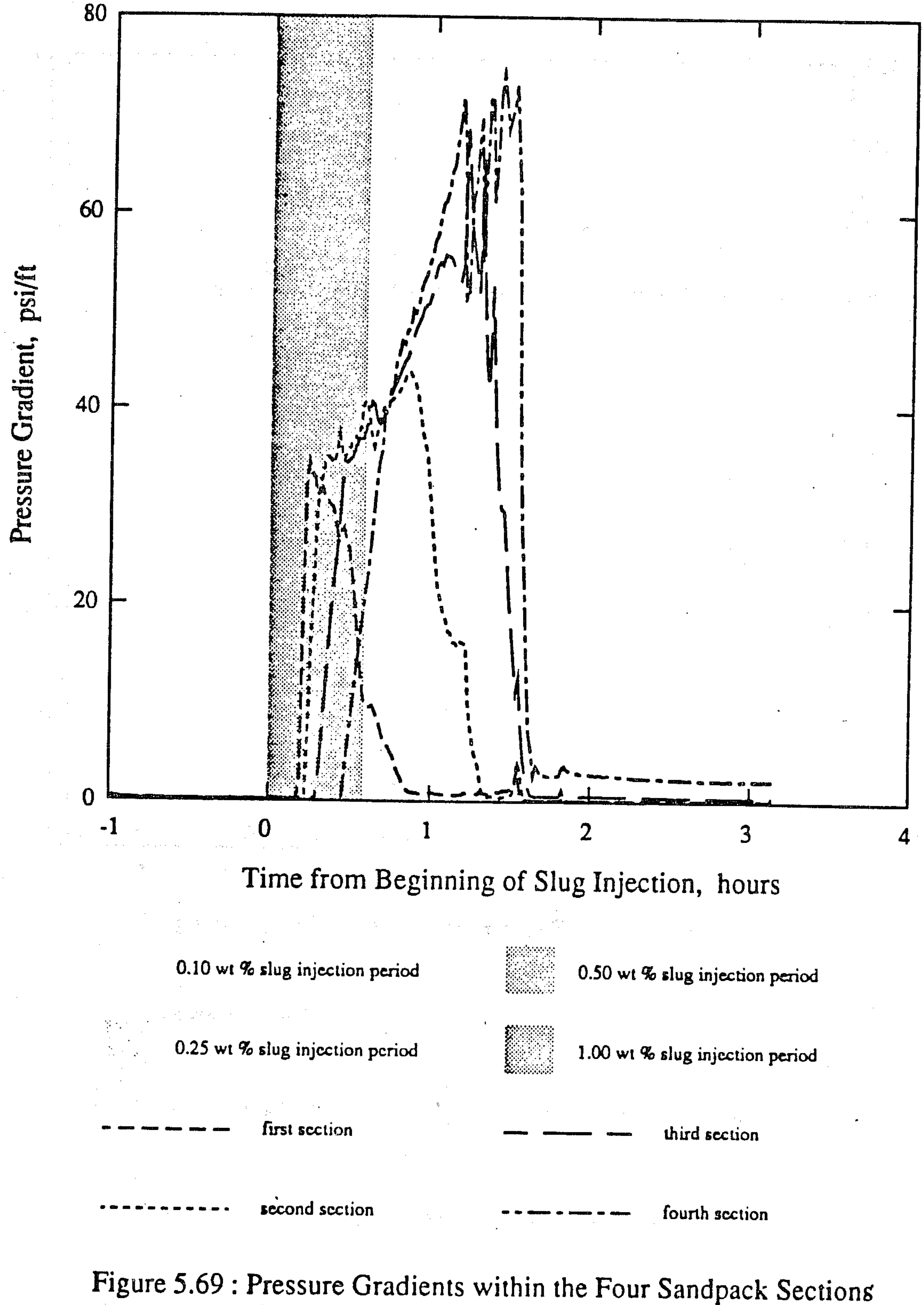

Figure 5.69 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of One Slug of Shell Enordet LXS 16 - Run 26

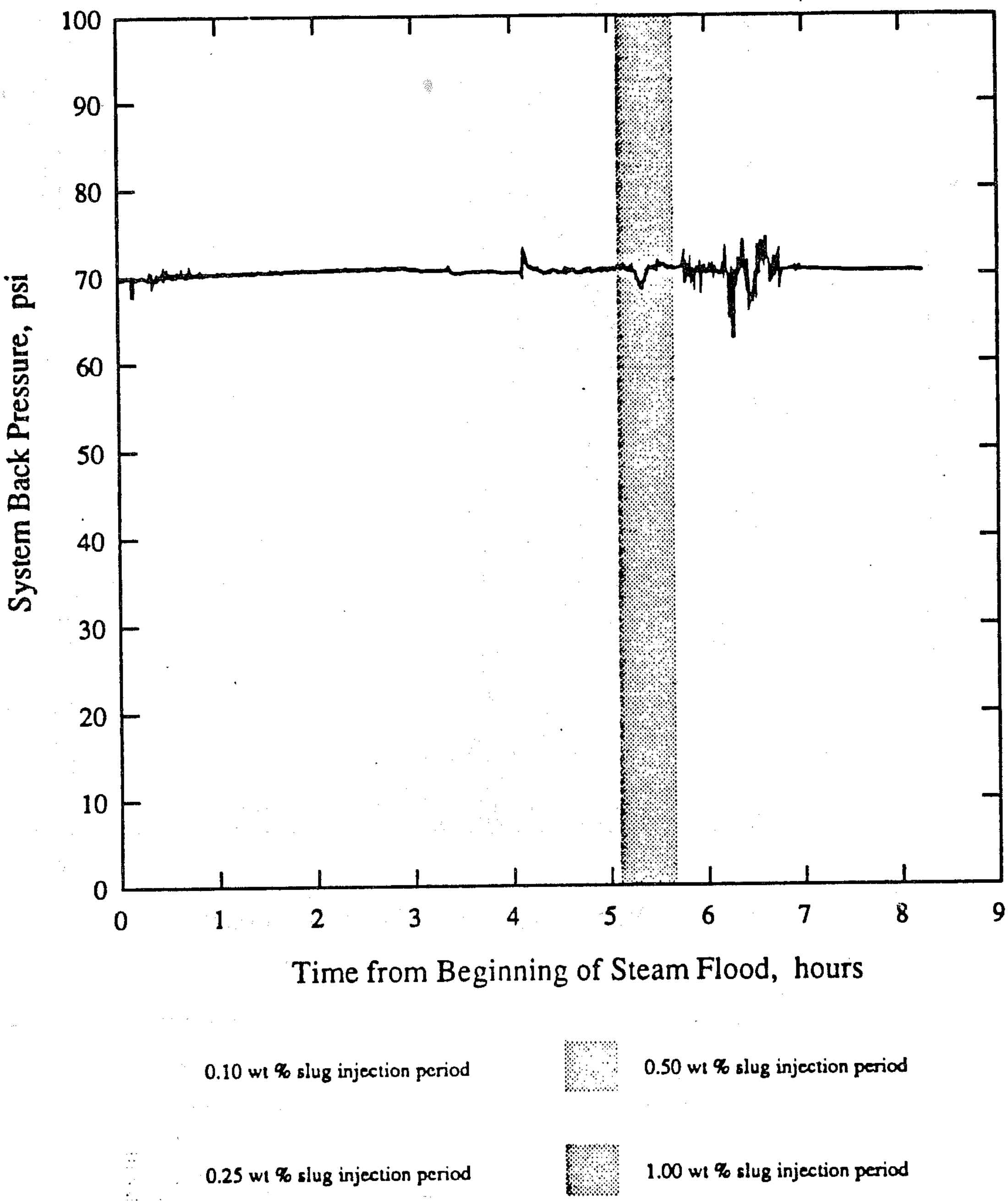

Figure 5.70 : System Back Pressure during Run 26

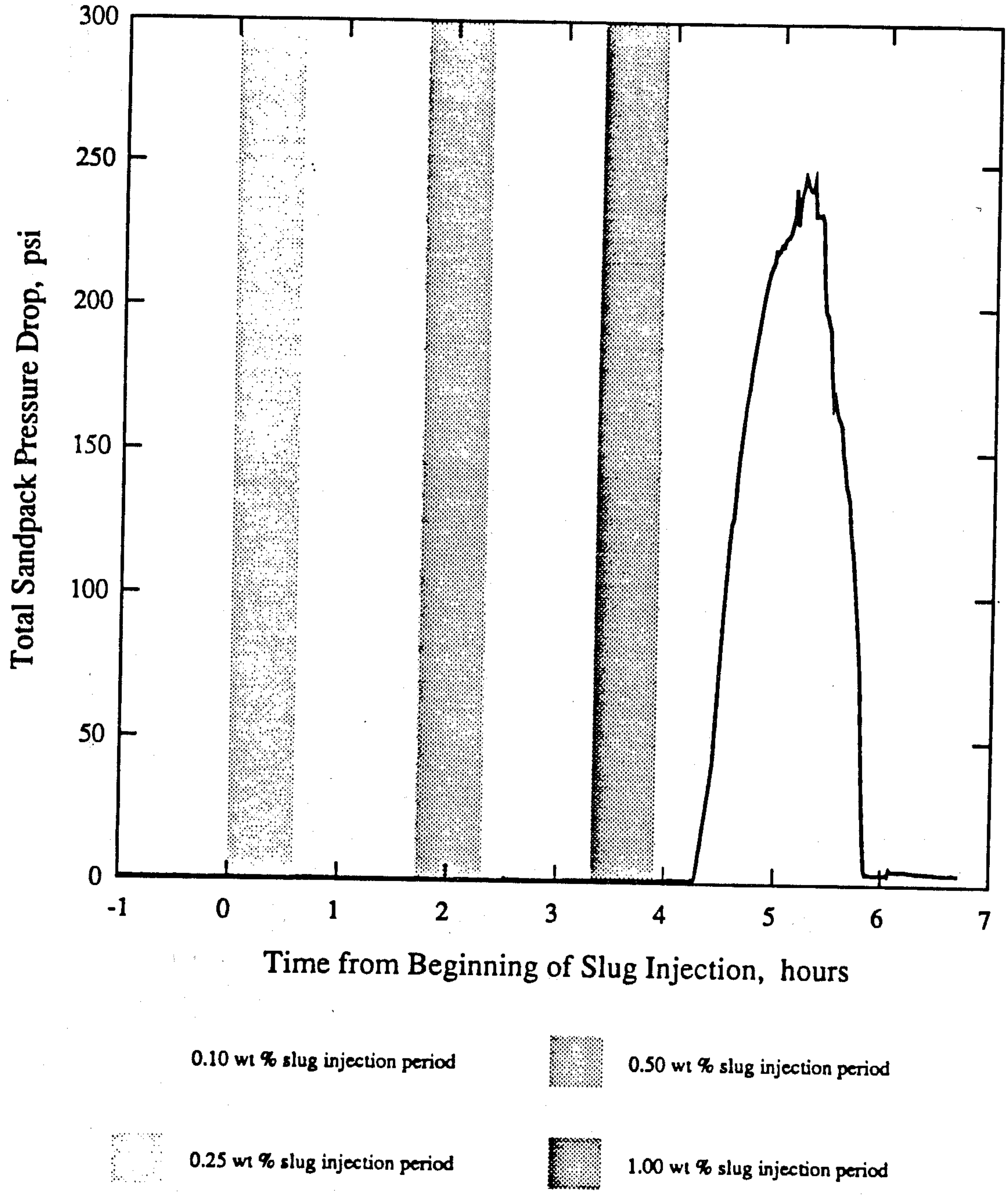

Figure 5.71 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet LXS 18 - Run 17

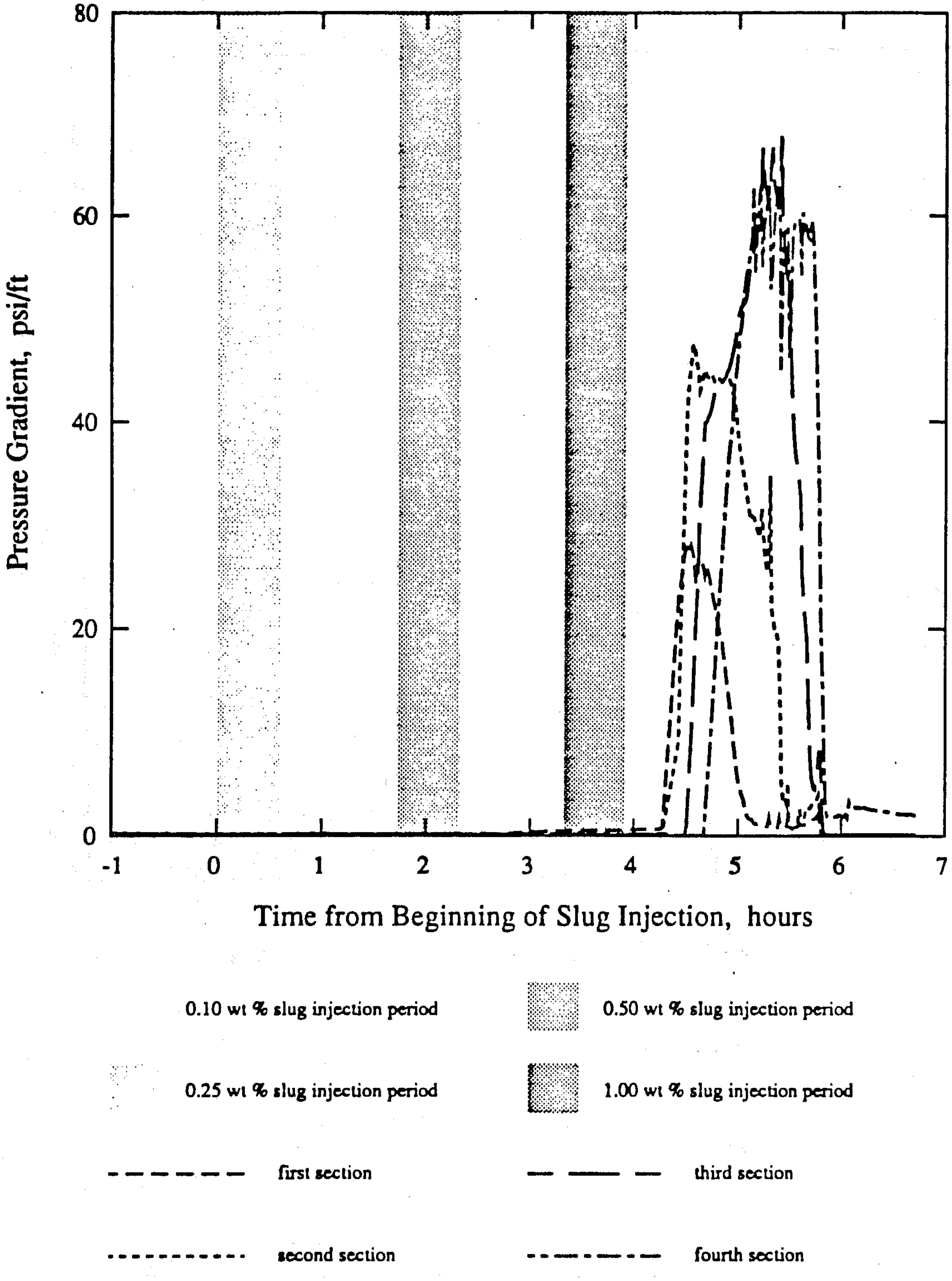

Figure 5.72 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Shell Enordet LXS 18 - Run 17

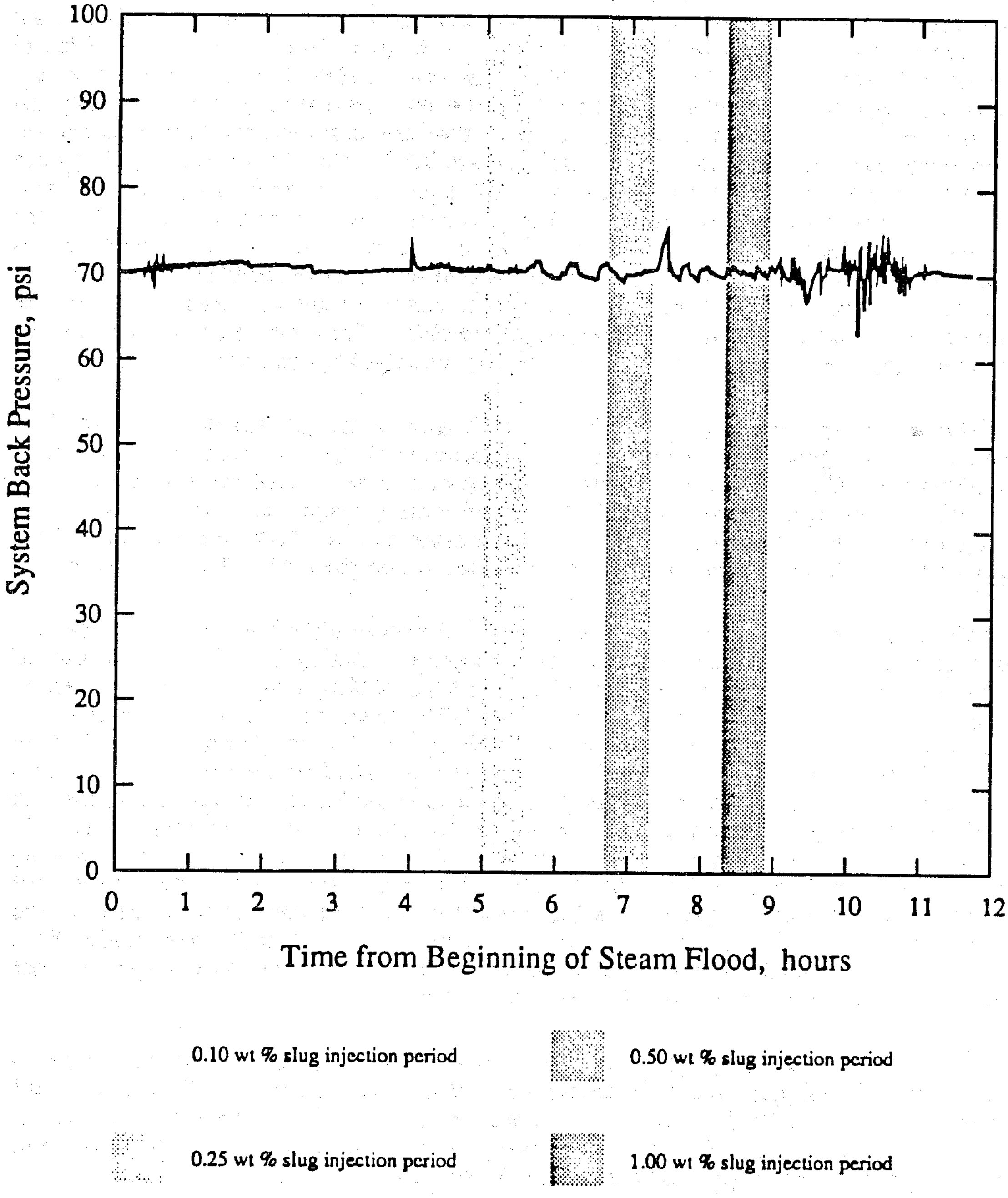

Figure 5.73 : System Back Pressure during Run 17

5.4. THE IMPORTANCE OF THE PRESENCE OF A NONCONDENSIBLE GAS

The stability of the steam foam depends upon the rate at which the individual foam bubbles collapse. Because the pressure within the smaller bubbles will be higher than within their larger counterparts, the steam will have a tendency to migrate from the smaller bubbles to neighbouring larger ones. As Janssen-Van Rosmalen *et al* (1985) observed, in order for the steam to migrate from one bubble to another the steam must pass through the liquid film that separates them. If the bubbles contain steam alone then the migration mechanism is simple; the condensation of steam on the lamellae inside the smaller bubble will liberate heat that when passed through the lamellae will vapourize an equal amount of water on its other side, thus generating steam within the larger bubble. The migration rate is therefore controlled by the rate at which heat is transferred through the lamellae. However, if a noncondensible gas is present in the bubble then the gas must actually diffuse through the lamellae in order for the smaller bubble to collapse. The addition of the noncondensible gas to a steam foam system therefore tends to stablize the foam by changing the bubble-collapse rate process from one that is predominantly a heat transfer controlled one, to one controlled by diffusion.

Using an experimental apparatus similar to that used in the present study, Janssen-Van Rosmalen *et al* investigated the importance of noncondensible gas in stablizing steam foam. The workers injected a 0.5 percent by weight solution of a linear toluene sulphonate surfactant into a pack of clean sand. Simultaneously 90 percent quality steam and 1 percent by volume of nitrogen were injected. At a steam saturation temperature of 150°C the presence of the nitrogen increased the maximum pressure drop observed within the sandpack by 47 percent.

To confirm the reported benefits of the presence of a noncondensible gas, an experimental run was performed during which nitrogen was not injected. During Run 25, the injection of two slugs of a 0.10 wt % solution of Shell's Enordet AOS 2024 was followed by the injection of a 0.25 wt % slug of the same surfactant. Figure 5.74 shows the variation in the sandpack pressure drop with time during the experiment. Foaming was observed in response to all three slugs. In addition, the diagram also shows that the foam collapsed immediately upon the stopping of surfactant injection. The maximum pressure drop observed in response to the injection of the slugs did not increase significantly with succeeding slugs. The maximum pressure drop generated by the first slug was 88 psi while the second slug, at the same concentration, only generated a pressure drop of 105 psi (Table 5.19). The results from testing other surfactants with nitrogen being injected is that succeeding injection of slugs typically increase the observed pressure drop by about a factor of two. Similarly, increasing the surfactant concentration from 0.10 to 0.25 wt % would normally be expected to increase the pressure response more significantly than the modest increase observed during Run 25.

Following injection of the first two slugs, foam did not completely collapse. In fact a pressure drop of 21 psi was maintained across the sandpack for 90 minutes following injection of the second slug. Figure 5.75 shows that it was long-lived foam in the sandpack's fourth section that was largely responsible for this extended pressure response. The diagram also shows that foam was generated in all four sandpack sections.

Figure 5.76 compares the pressure response curves for the cases of injection of a single slug of 0.1 wt % AOS 2024 either with or without nitrogen injection. The time scales have been suitably adjusted so that slug injection begins at $t = 0$ hr. this diagram clearly indicates that the rate of increase in the pressure drop is much less when nitrogen is absent. Also, in the absence of nitrogen, the foam collapses immediately upon the stopping of surfactant injection whereas when accompanied by injection of nitrogen foam persisted for another 49 minutes. Also, the maximum pressure drop attained across the pack was just 88 psi in the absence of

Table 5.19 : Summary of Pressure Response Data for Shell Enordet AOS 2024 in Absence of Nitrogen (Run 25)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	0.25	--
Slug Injection					
Start Time (hr)		4.680	6.879	8.979	--
Stop Time (hr)		5.271	7.472	9.569	--
Duration (min)		35.4	35.6	35.4	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	34.9	34.7	35.3	--
	Time (hr)	5.13	7.06	9.32	--
Section 2	ΔP_2 (psi)	36.3	37.6	39.2	--
	Time (hr)	5.28	7.49	9.61	--
Section 3	ΔP_3 (psi)	31.5	55.3	54.9	--
	Time (hr)	5.33	7.54	9.66	--
Section 4	ΔP_4 (psi)	10.1	25.4	39.4	--
	Time (hr)	5.37	7.64	9.70	--
Entire Tube	ΔP (psi)	88.1	105.0	124.2	--
	Time (hr)	5.28	7.49	9.60	--
Duration of Pressure Response†					
Section 1	Time (min)	42	42	45	--
Section 2	Time (min)	28	37	39	--
Section 3	Time (min)	20	26	37	--
Section 4	Time (min)	8	27 **	18	--
Entire Tube	Time (min)	67 **	? **	45	--
Response Time Lag (min)		3	2	4	--

† Duration of pressure response as defined in Section 5.2.

** Foam did not collapse completely before injection of next slug. Duration listed is therefore a minimum value only.

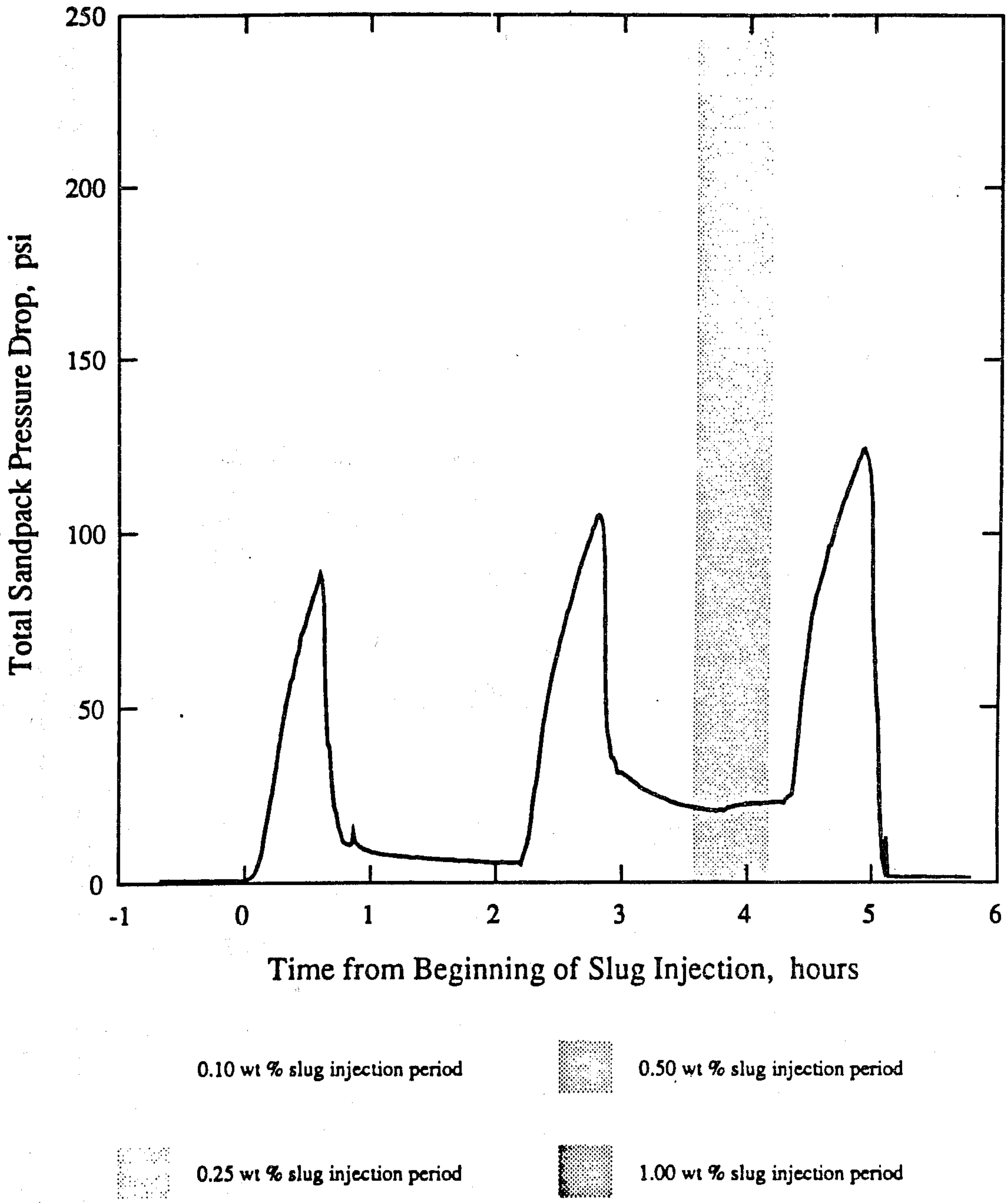

Figure 5.74 : Total Pressure Drop Response to Injection of Three Slugs of Shell Enordet AOS 2024 in Absence of Nitrogen - Run 25

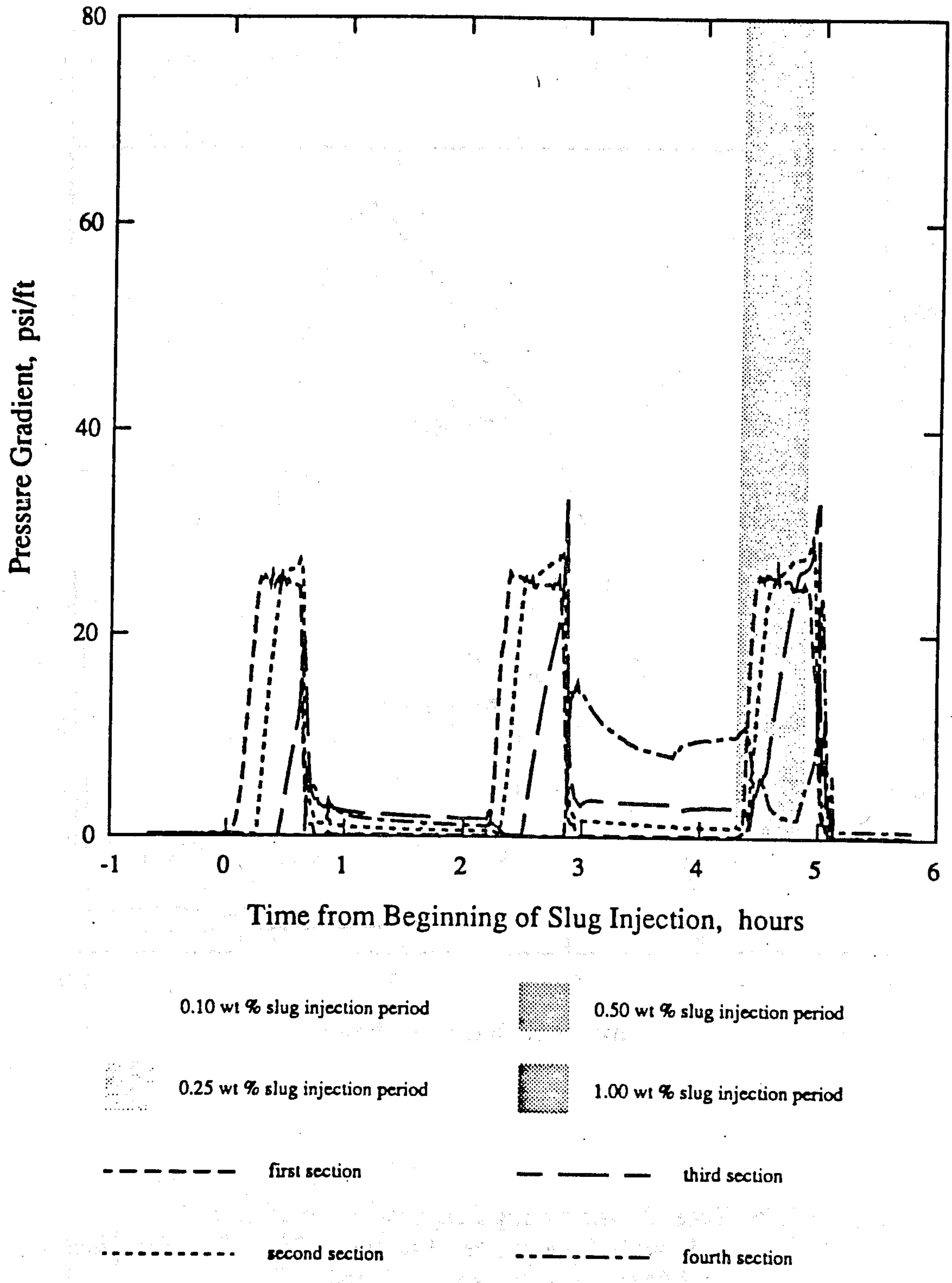

Figure 5.75 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Three Slugs of Shell Enordet AOS 2024 in Absence of Nitrogen - Run 25

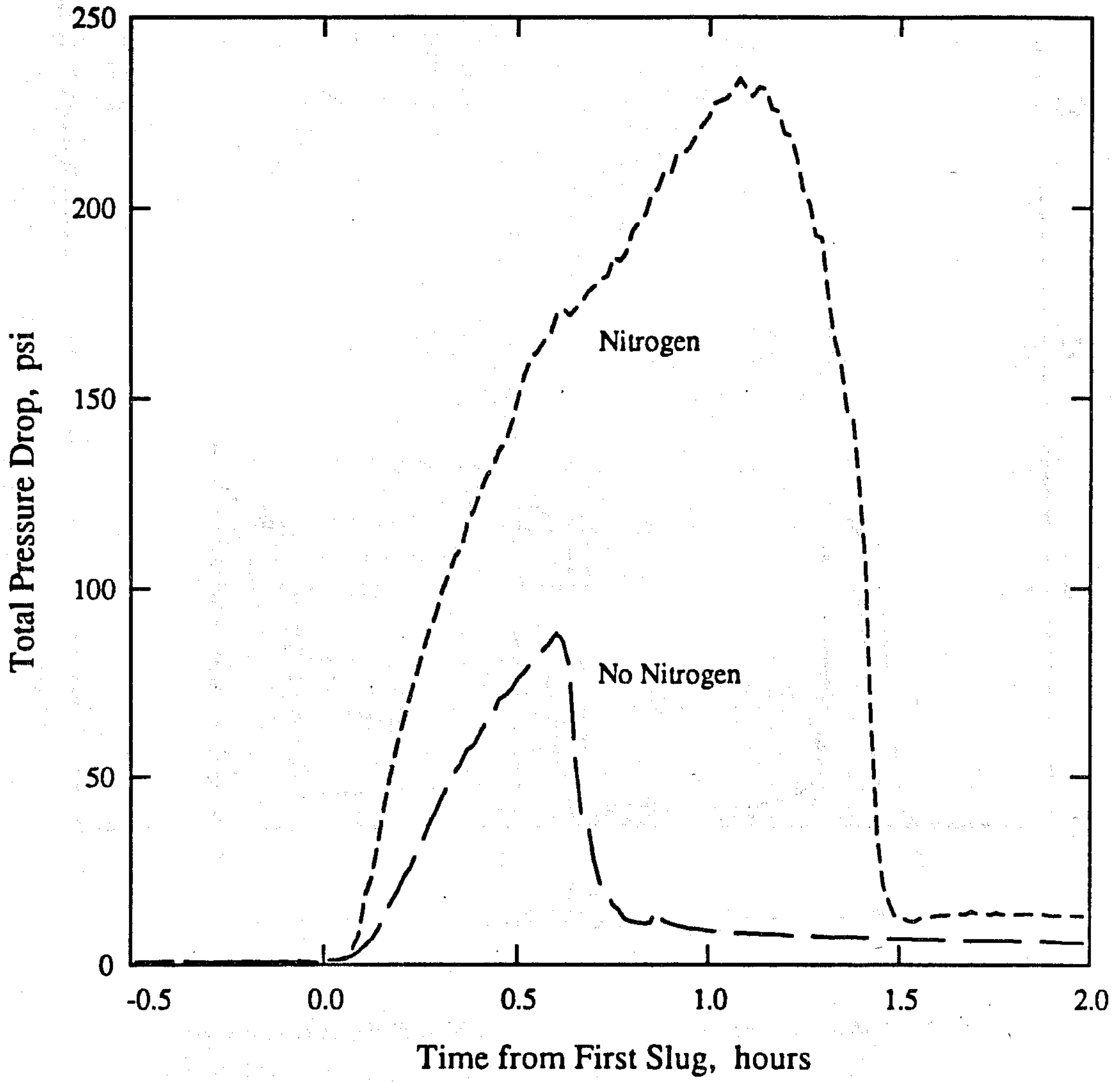

Figure 5.76 : Total Pressure Drop Response to Injection of a 0.10 wt % Slug of Shell Enordet AOS 2024 in Presence and Absence of the Noncondensible Gas

the non-condensible gas, compared to 234 psi in its presence. These results tend to indicate that the rate of foam collapse was much faster in the absence of the non-condensible gas.

The variations in the pressure drops across each of the four sections are compared for the two experiments in Figures 5.77 to 5.80. Figure 5.77 shows that foaming begins to occur within the first section at about the same time for the two cases. However, in the absence of nitrogen the rate of increase in the pressure drop is less and the maximum value observed is 35 psi compared to 52 psi in the presence of the non-condensible gas. Once a maximum pressure drop is reached however, it is maintained at the value instead of decreasing. Figure 5.78 shows that foaming begins later in the absence of the non-condensible gas suggesting that the speed at which the foam front advances through the sandpack is slower. This observation is supported by similar features of the next two diagrams. The sudden increases in the pressure drops in the third and fourth sections at t = 0.63 hr (Figures 5.79 and 5.80) may be due to the sudden variations in the back pressure observed at that time. Thus the foam generated at this time may have been induced rather than spontaneously formed.

The preceding results therefore tend to confirm the conclusions of the work of Janssen-Van Rosmalen *et al* (1985). The presence of a non-condensible gas such as nitrogen tends to stabilize the foam and decreases the rate of foam decay.

In the absence of nitrogen, during injection of the three slugs the pressure at the outlet end of the sandpack fell significantly below 70 psig (Figure 5.81). The pressure began to fall below 70 psig as soon as foaming commenced upstream and only retuned to 70 psig after the foam had collapsed. During these periods, the back pressure regulator was in perfect working order, no fluids were produced at the outlet, and there were no leaks from the system.

The fall off in the outlet pressure was caused by the condensation of some of the steam, driven by heat losses from the tube. The following calculations serve to illustrate how this could occur. Consider a one litre container filled with 100 percent quality saturated steam at 158°C. At this temperature, the steam saturation pressure is 70.6 psig (558 kPa).

Assuming steam behaves as an ideal gas, the density, ρ_{steam}, is given by:

$$\rho_{steam} = \frac{P\ M}{R\ T}$$

where, M is the molecular weight of steam,

and, R is the universal gas constant.

$$Thus, \quad \rho_{steam} = \frac{(5.88 \times 10_3\ Pa)\ (0.018016\ kg/g{-}mol)}{(98.3143\ J/Kg{-}mol)\ ((158 + 273.2)\ K)} = 2.95\ kg/m_3$$

Hence a one litre volume contains 2.95×10^{-3} kg of steam.

Now suppose that ten percent of the steam condenses due to loss of heat from the container. the mass of water will be 0.295×10^{-3} kg and will have a density of 942 kg/m^3 under these conditions (saturated water between 155° and 160°C). The water will therefore occupy a 0.0003 litre volume, leaving 0.9997 litres fr the remaining 2.65×10^{-3} kg of steam. Again, assuming the ideal gas law is obeyed,

$$\frac{P}{T} = \frac{(2.65 \times 10^{-3}\ kg)\ (8.3143\ J/Kg{-}mol)}{(0.018016\ kg/g{-}mol)\ (0.9997 \times 10^{-3}\ m^3)} = 1230\ Pa/K$$

where P and T are the steam saturation pressure (in pa) and temperature (in K) under the new

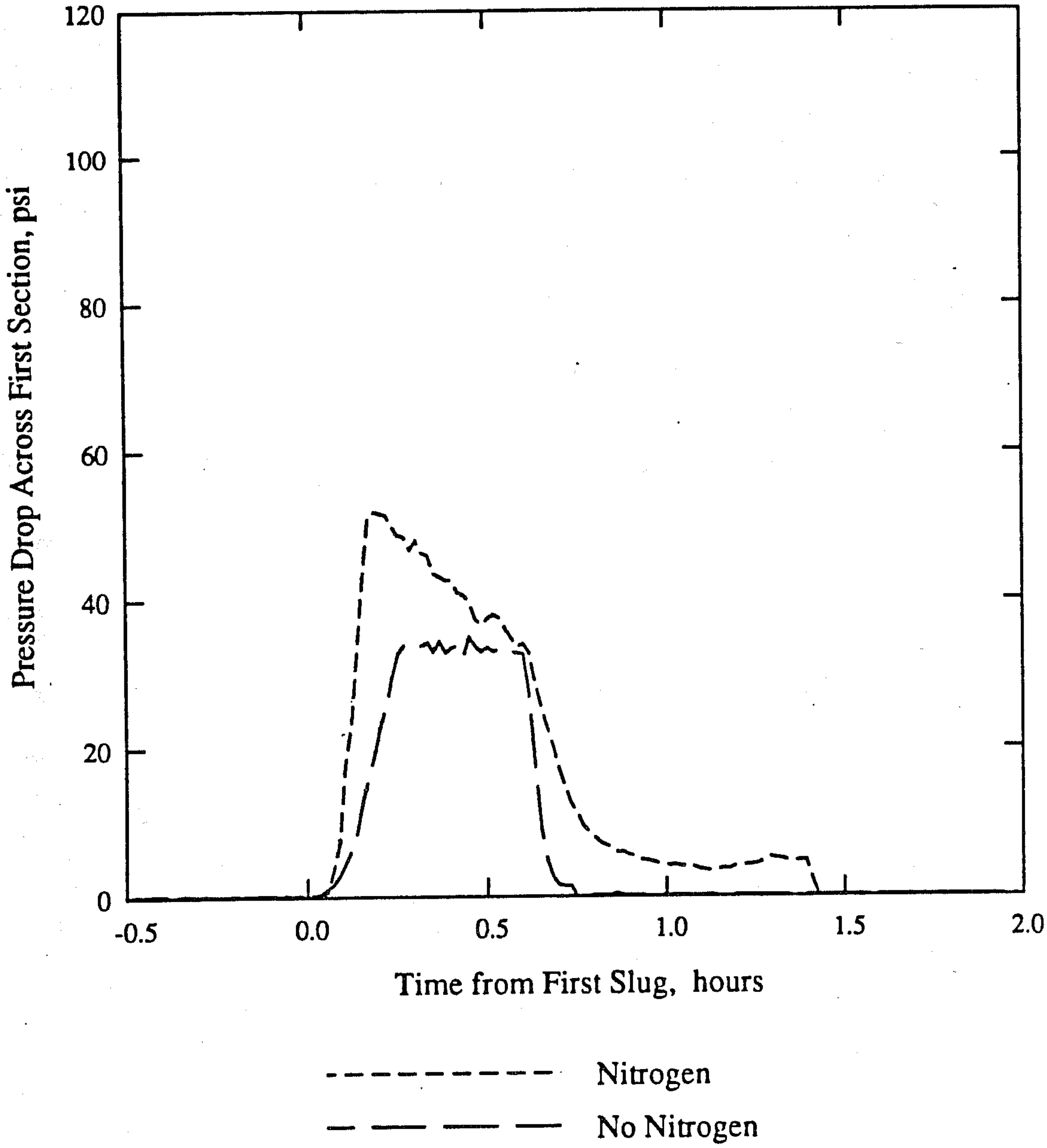

Figure 5.77 : Pressure Drop Across First Sandpack Section in Response to Injection of 0.10 wt % Slug of Shell Enordet AOS 2024 in Presence and Absence of the Noncondensible Gas

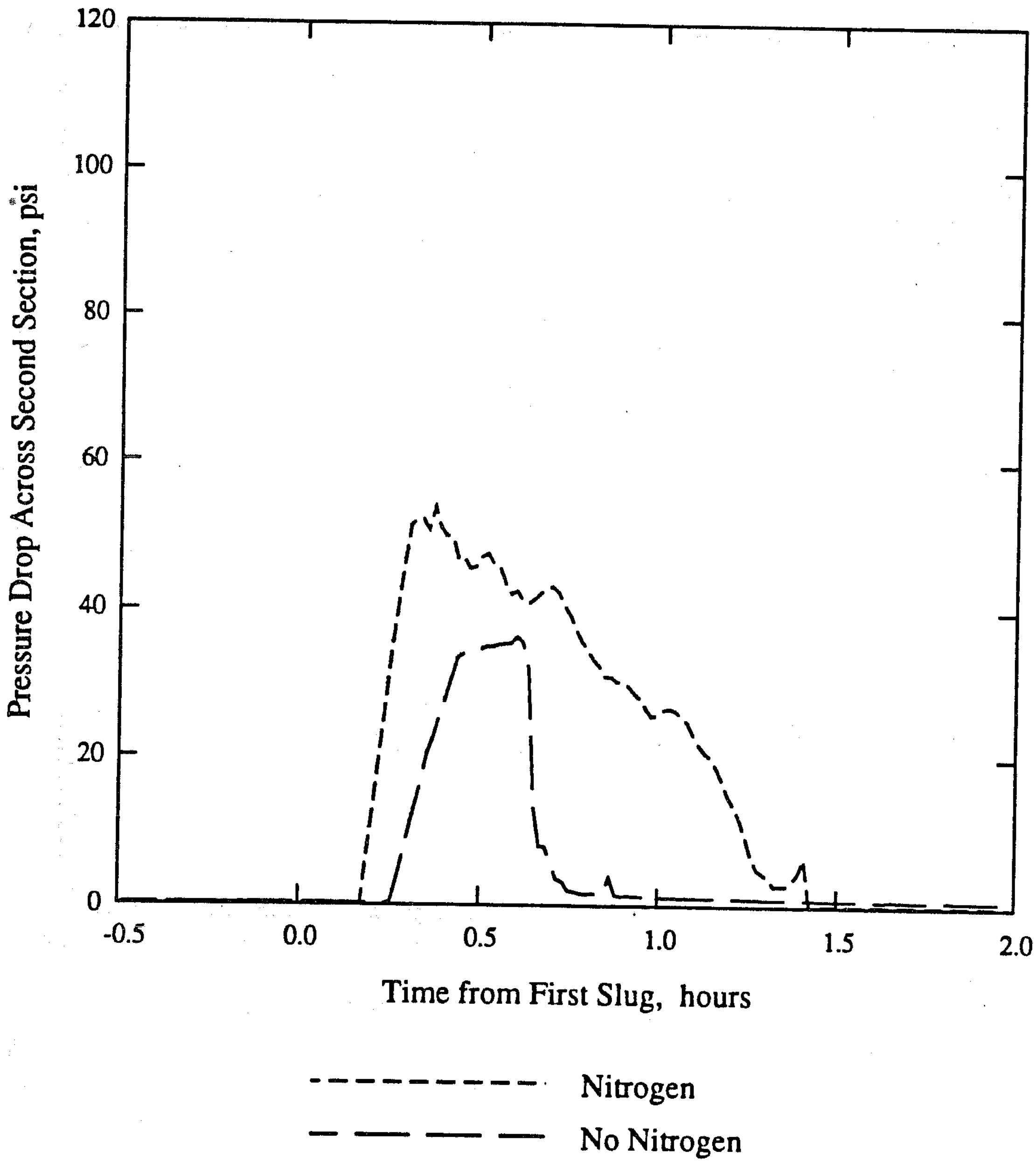

Figure 5.78 : Pressure Drop Across Second Sandpack Section in Response to Injection of 0.10 wt % Slug of Shell Enordet AOS 2024 in Presence and Absence of the Noncondensible Gas

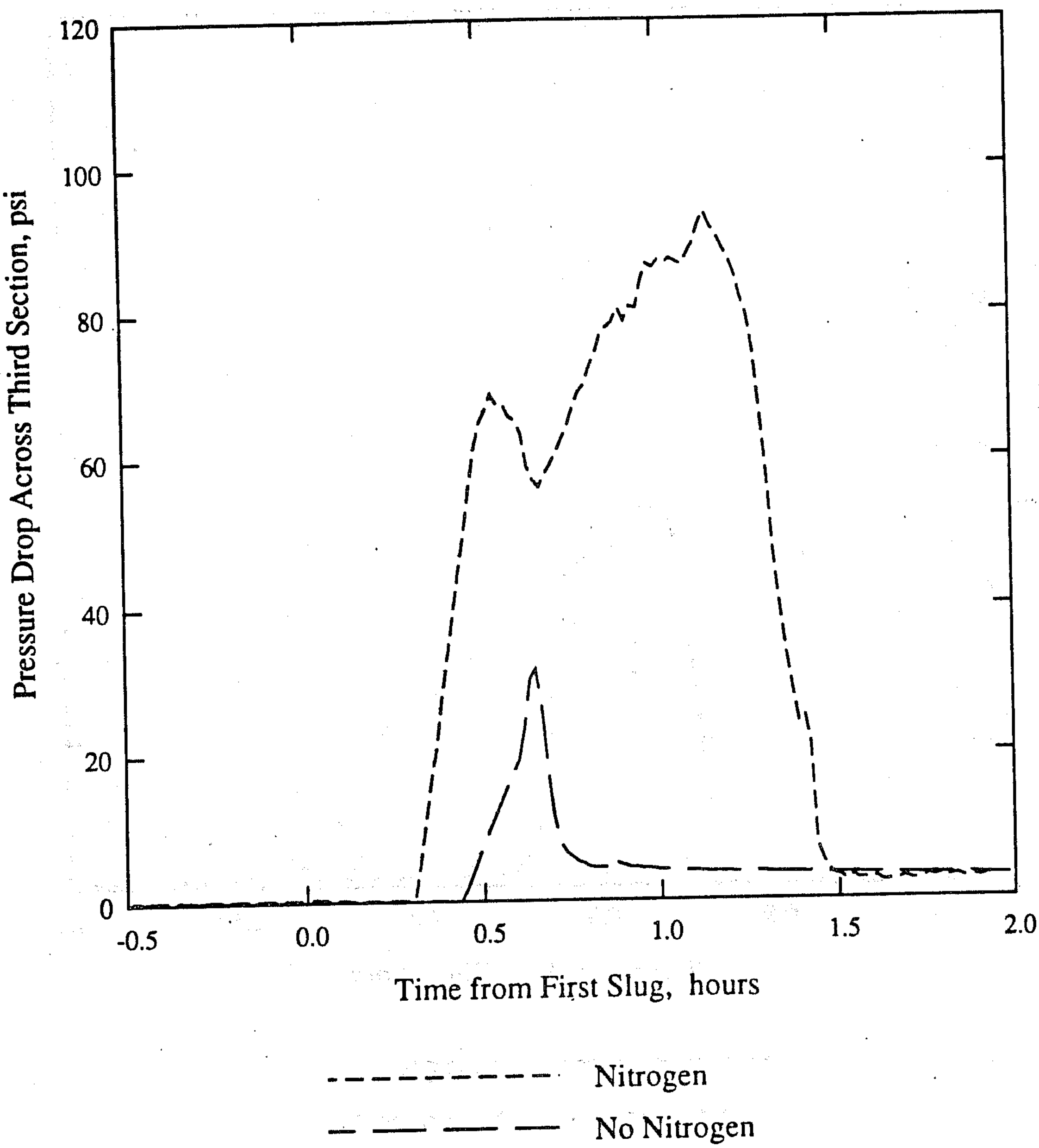

Figure 5.79 : Pressure Drop Across Third Sandpack Section in Response to Injection of 0.10 wt % Slug of Shell Enordet AOS 2024 in Presence and Absence of the Noncondensible Gas

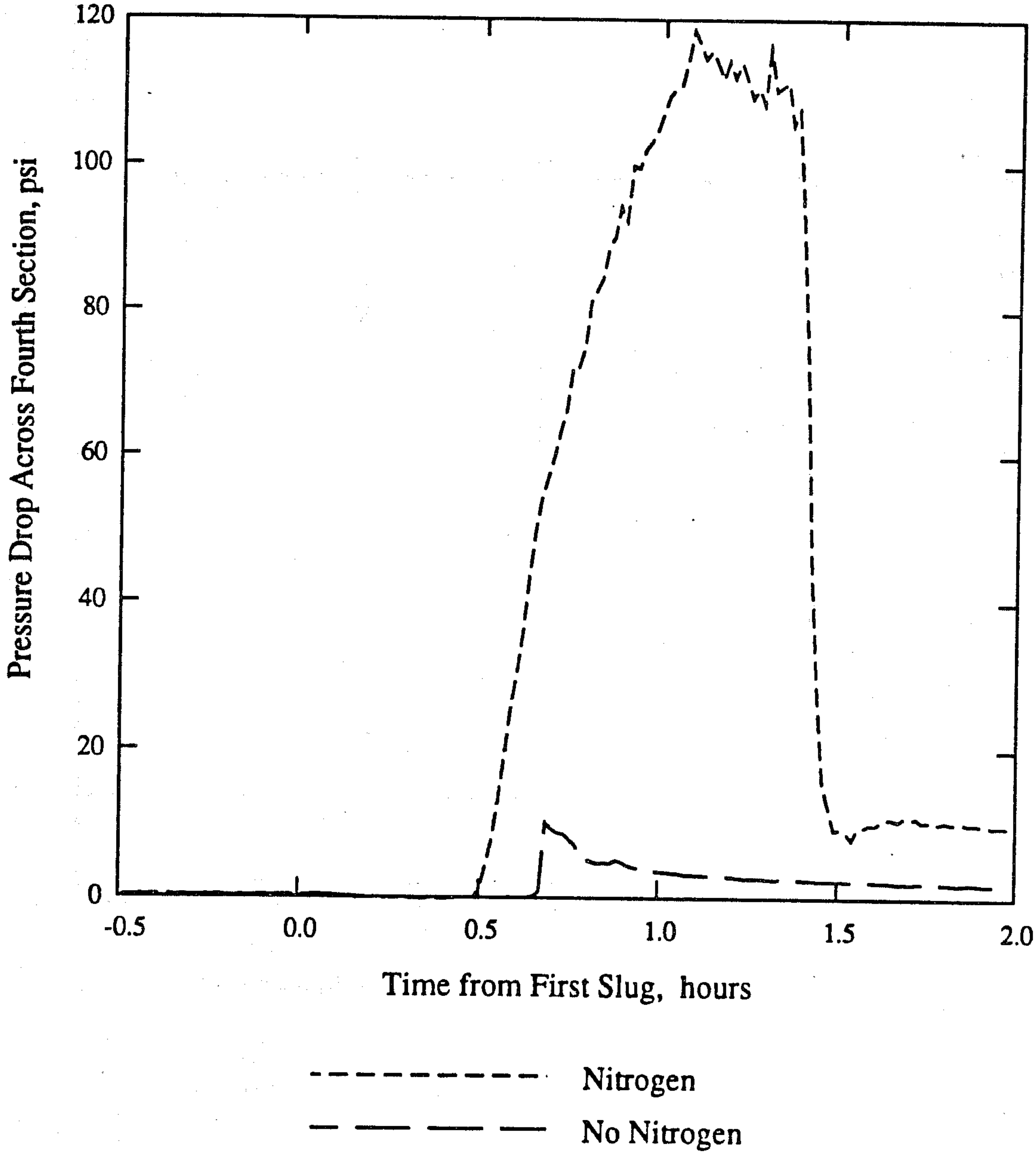

Figure 5.80 : Pressure Drop Across Fourth Sandpack Section in Response to Injection of 0.10 wt % Slug of Shell Enordet AOS 2024 in Presence and Absence of the Noncondensible Gas

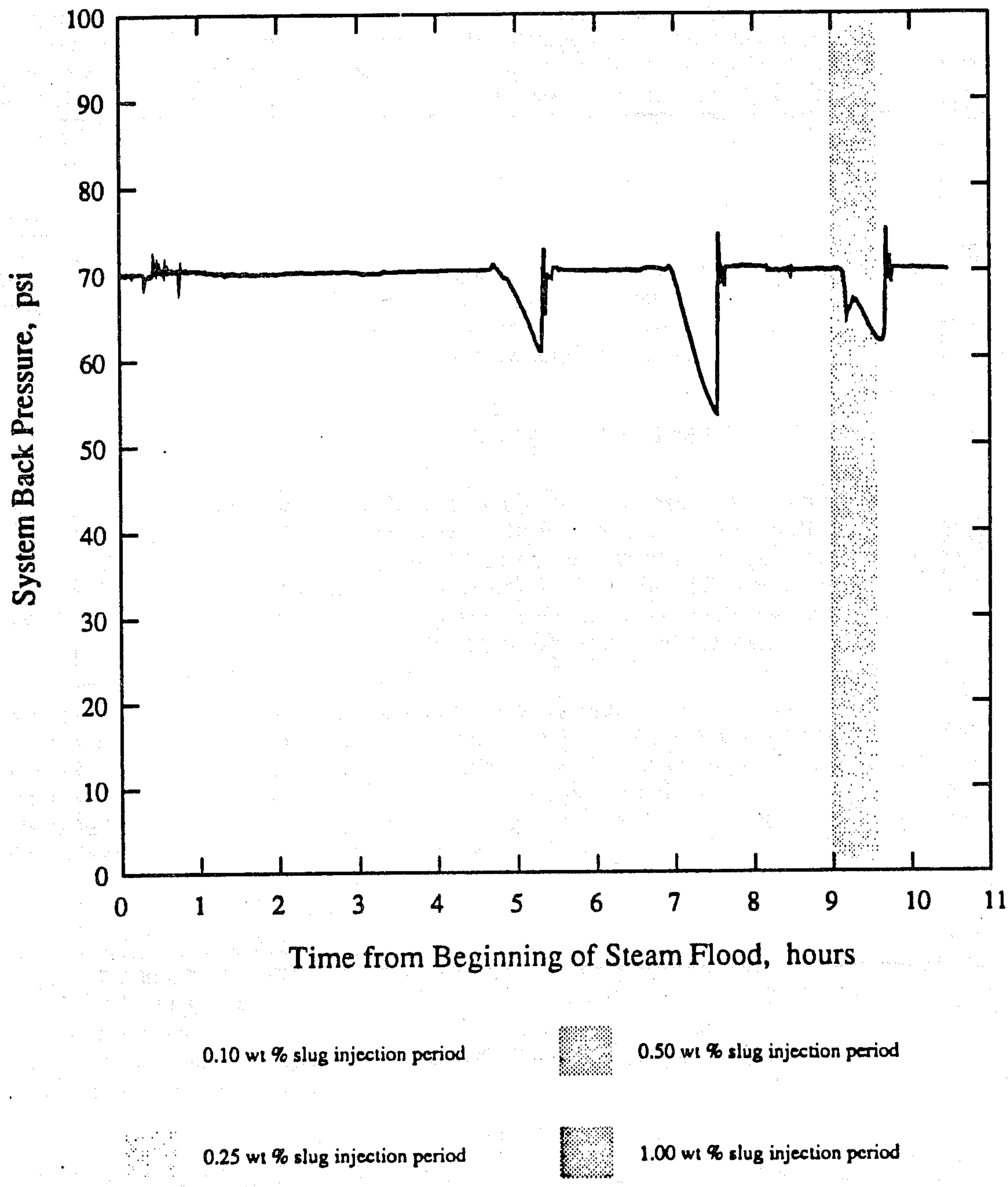

Figure 5.81 : System Back Pressure during Run 25

steam conditions. There will a unique set of conditions for each value of P/T: for 1230 Pa/K this occurs when P = 522 kPa (61.0 psig) and T = 426.6 K (153.4°C).

Returning now to the sandpack model, the aggressive foaming in the upstream section of the pack would have resulted in a blockage forming which would have significantly reduced the amount of steam flowing into the downstream sections well below the 4 ml/min cwe being injected into the system. Thus, the condensation of just ten percent of the steam would have resulted in a drop in the outlet pressure to 61.0 psig as was observed in response to injection of the first slug (Figure 5.81).

In most cases when nitrogen was injected with the surfactant such fall offs in the outlet pressure were not observed as the partial pressure of the nitrogen, downstream of the foam increased to compensate for the decrease in the steam partial pressure. During several runs however (e.g. Run 30), a similar decrease in the outlet pressure was observed. In these case, the blockage caused by the foams generated were so effective that the rates of flow of both the steam and nitrogen to the downstream sections were severly restricted.

5.5. VARIATION IN SYSTEM BACK PRESSURE

Two experiments were performed to study the effect of varying the system back pressure. During Run 31 two slugs of a 0.10 wt % solution of Shell's Enordet AOS 1618 surfactant were injected against a back pressure of 100 psig. A single slug of the same solution was injected during Run 32 with the back pressure set at 40 psig. The surfactant solution used during these runs was the same as that used during Run 30 when a single 0.10 wt % slug was injected against the standard back pressure of 70 psig.

During Run 31 two 0.10 wt % slugs were injected against 100 psig. Figure 5.82 shows the variation in total pressure drop across the sandpack as a function of time. The maximum pressure drops observed in response to the two slugs were 57 psi and 158 psi respectively (Table 5.20). Figure 5.83 shows that in response to the first slug, foaming did not occur in the fourth section, yet foam generated a pressure drop of 100 psi in this section in response to the second slug. Figure 5.84 presents the back pressure behaviour that was observed during this run.

Only a single slug of the surfactant solution was injected during Run 32, as this resulted in a maximum pressure drop in excess of 300 psi (Figure 5.85). The foam generated in the fourth section caused the pressure transducer in that section to overrange. Figure 5.86 shows the variation in pressure gradients existing in the four sandpack sections. The trace for the fourth section clearly suggests that had the transducer not overranged a significantly higher pressure may have been recorded. The main pressure response data for this run is summarized in Table 5.21.

During the production of foam from the system considerable difficulty was encountered in maintaining a constant back pressure (Figure 5.87). It should be noted that the vertical scale of this diagram is expanded compared to those of previous back pressure diagrams.

A comparison of the responses to the injection of a single 0.1 wt % AOS 1618 slug at the three back pressures is presented diagrammatically in Figure 5.88 and in tabular form in Table 5.22. The diagram clearly shows that not only does the pressure drop increase with decreasing pressure, but so too does the response duration. This emphasizes the importance of

Table 5.20 : Summary of Pressure Response Data for for Shell Enordet AOS 1618 Against a back Pressure of 100 psig (Run 31)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	0.10	--	--
Slug Injection					
Start Time (hr)		6.004	8.197	--	--
Stop Time (hr)		6.594	8.793	--	--
Duration (min)		35.4	35.7	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	32.6	40.9	--	--
	Time (hr)	6.26	8.35	--	--
Section 2	ΔP_2 (psi)	46.8	55.7	--	--
	Time (hr)	6.44	8.48	--	--
Section 3	ΔP_3 (psi)	37.2	85.2	--	--
	Time (hr)	6.75	9.01	--	--
Section 4	ΔP_4 (psi)	--	100.2	--	--
	Time (hr)	--	9.22	--	--
Entire Tube	ΔP (psi)	56.6	158.1	--	--
	Time (hr)	6.40	9.01	--	--
Duration of Pressure Response†					
Section 1	Time (min)	78	38	--	--
Section 2	Time (min)	84	47	--	--
Section 3	Time (min)	48	51	--	--
Section 4	Time (min)	--	37	--	--
Entire Tube	Time (min)	> 84	63	--	--
Response Time Lag (min)		6	6	--	--

† Duration of pressure response as defined in Section 5.2.

Table 5.21 : Summary of Pressure Response Data for for Shell Enordet AOS 1618 Against a back Pressure of 40 psig (Run 32)

		Slug 1	Slug 2	Slug 3	Slug 4
Concentration (wt%)		0.10	--	--	--
Slug Injection					
Start Time (hr)		4.482	--	--	--
Stop Time (hr)		5.073	--	--	--
Duration (min)		35.4	--	--	--
Maximum Observed Pressure Drop					
Section 1	ΔP_1 (psi)	56.2	--	--	--
	Time (hr)	4.66	--	--	--
Section 2	ΔP_2 (psi)	77.2	--	--	--
	Time (hr)	4.82	--	--	--
Section 3	ΔP_3 (psi)	124.8	--	--	--
	Time (hr)	5.74	--	--	--
Section 4	ΔP_4 (psi)	> 132 ‡	--	--	--
	Time (hr)	? ‡	--	--	--
Entire Tube	ΔP (psi)	> 302 ‡	--	--	--
	Time (hr)	5.71 ‡	--	--	--
Duration of Pressure Response†					
Section 1	Time (min)	57	--	--	--
Section 2	Time (min)	73	--	--	--
Section 3	Time (min)	77	--	--	--
Section 4	Time (min)	64	--	--	--
Entire Tube	Time (min)	96	--	--	--
Response Time Lag (min)		2	--	--	--

† Duration of pressure response as defined in Section 5.2.

‡ Transducers overranged during slug injection.

Table 5.22 : Comparsion of Pressure Data in Response to Injection of a Single 0.10 wt % Slug of Shell Enordet AOS 1618 Against Three Different Back Pressures

Experimental Run	32	30	31
Backpressure (psig)	40	70	100
Steam Saturation Temperature (°C)	142	158	170
Maximum Observed Pressure Drop			
Section 1 ΔP_1 (psi)	56.2	50.0	32.6
Section 2 ΔP_2 (psi)	77.2	66.4	46.8
Section 3 ΔP_3 (psi)	124.8	88.8	37.2
Section 4 ΔP_4 (psi)	> 132	90.9	--
Entire Tube ΔP (psi)	> 302	131.9	56.6

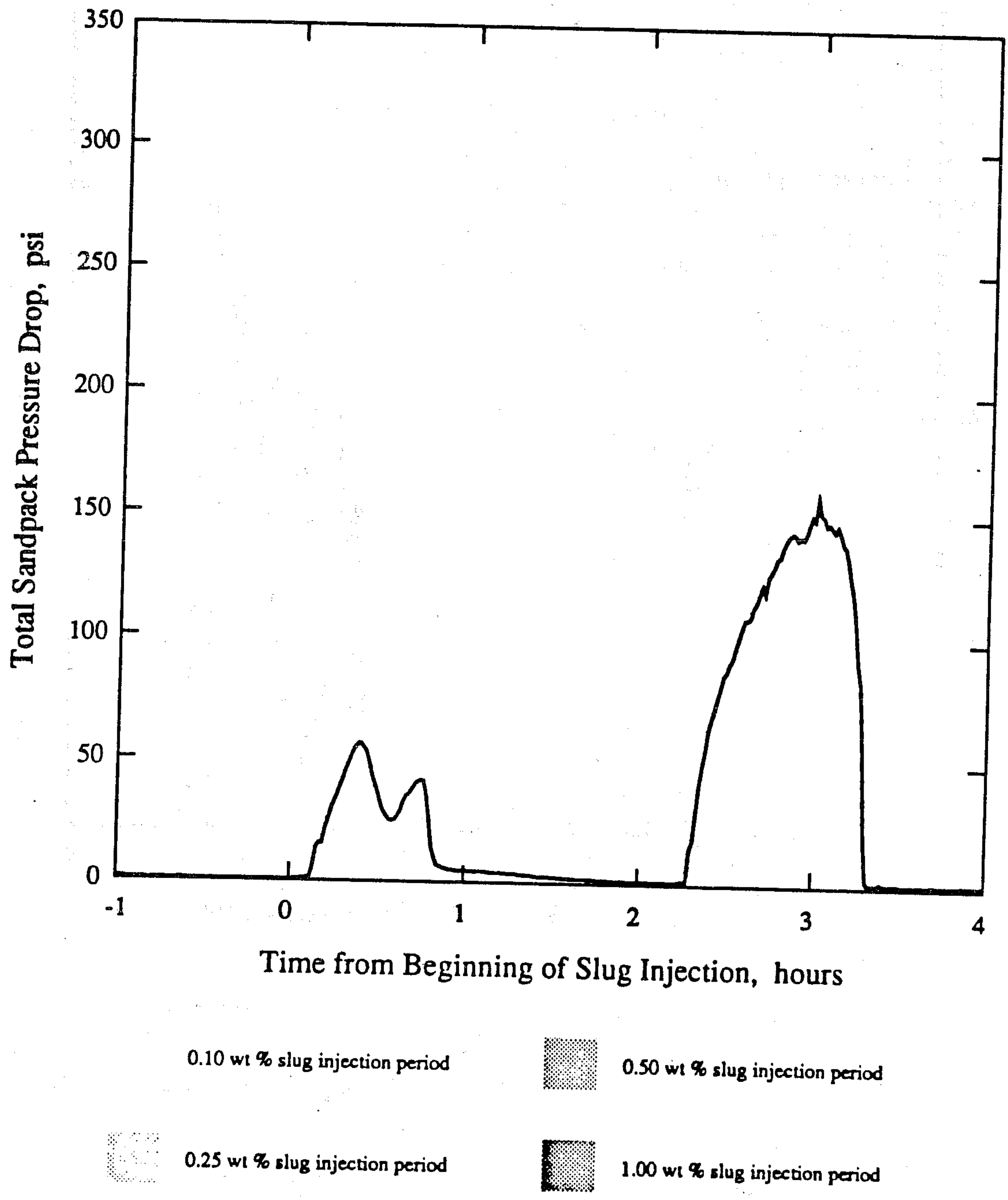

Figure 5.82 : Total Pressure Drop Response to Injection of Two Slugs of Shell Enordet AOS 1618 with Back Pressure at 100 psig - Run 31

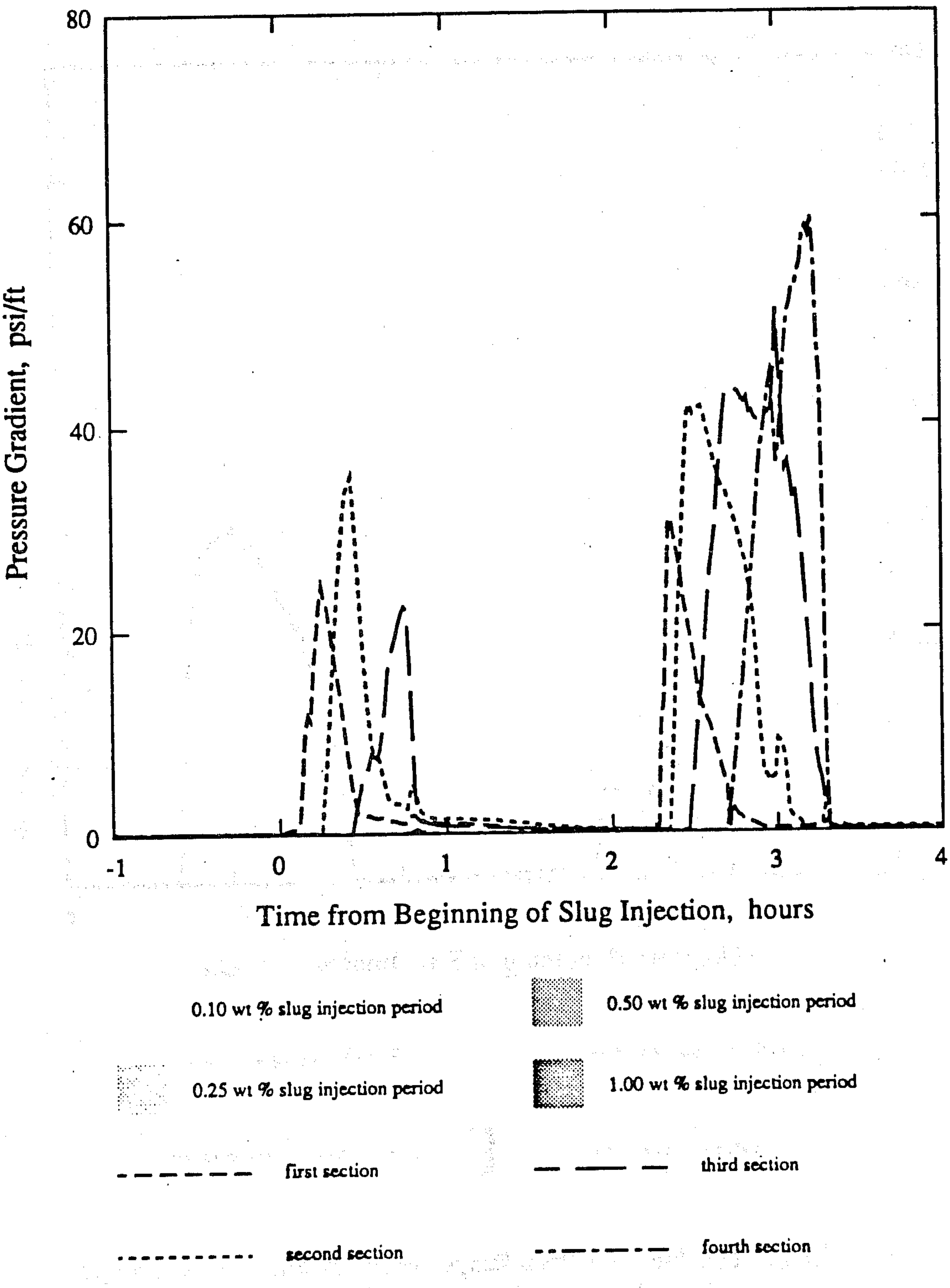

Figure 5.83 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of Two Slugs of Shell Enordet AOS 1618 - Run 31

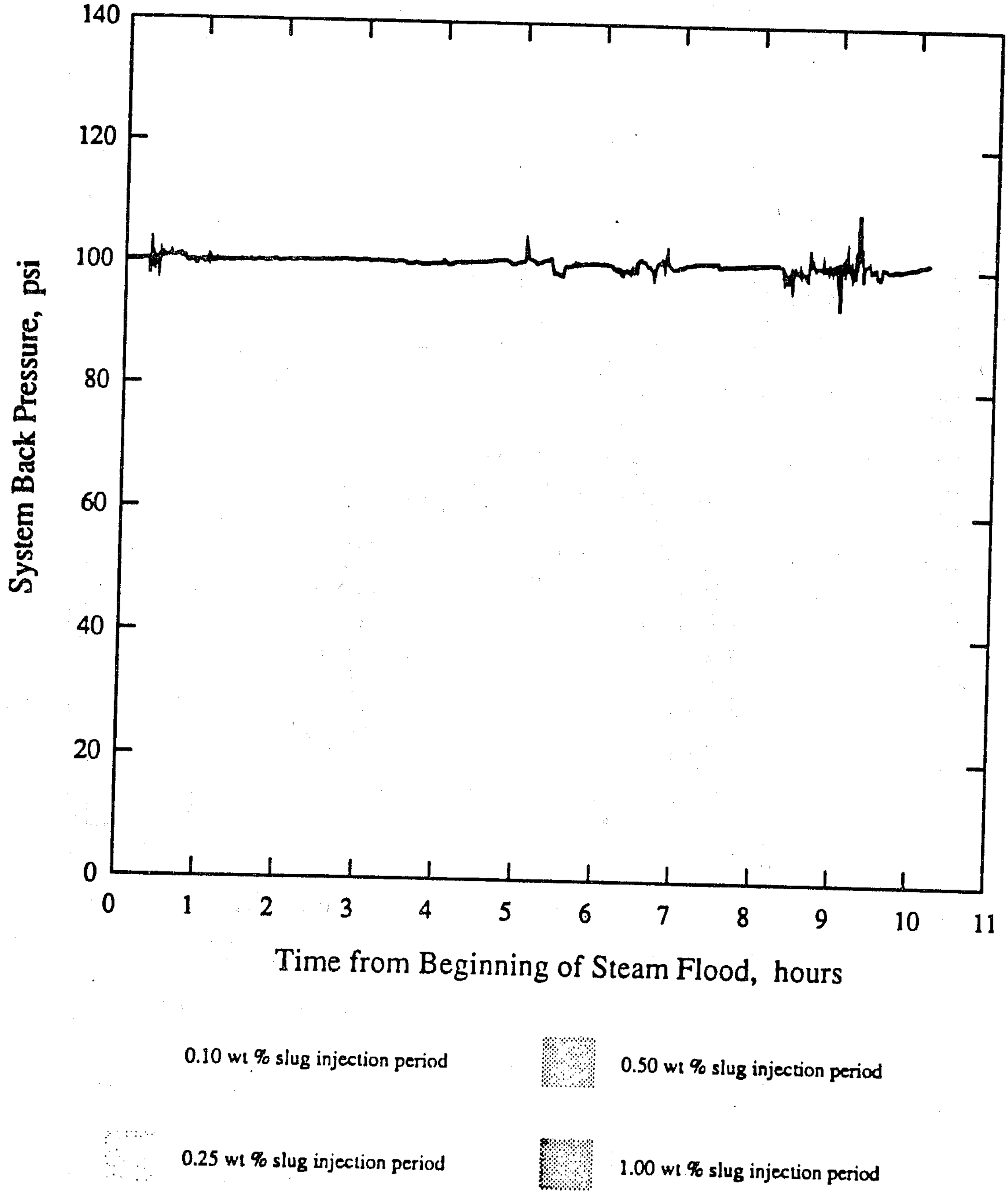

Figure 5.84 : System Back Pressure during Run 31

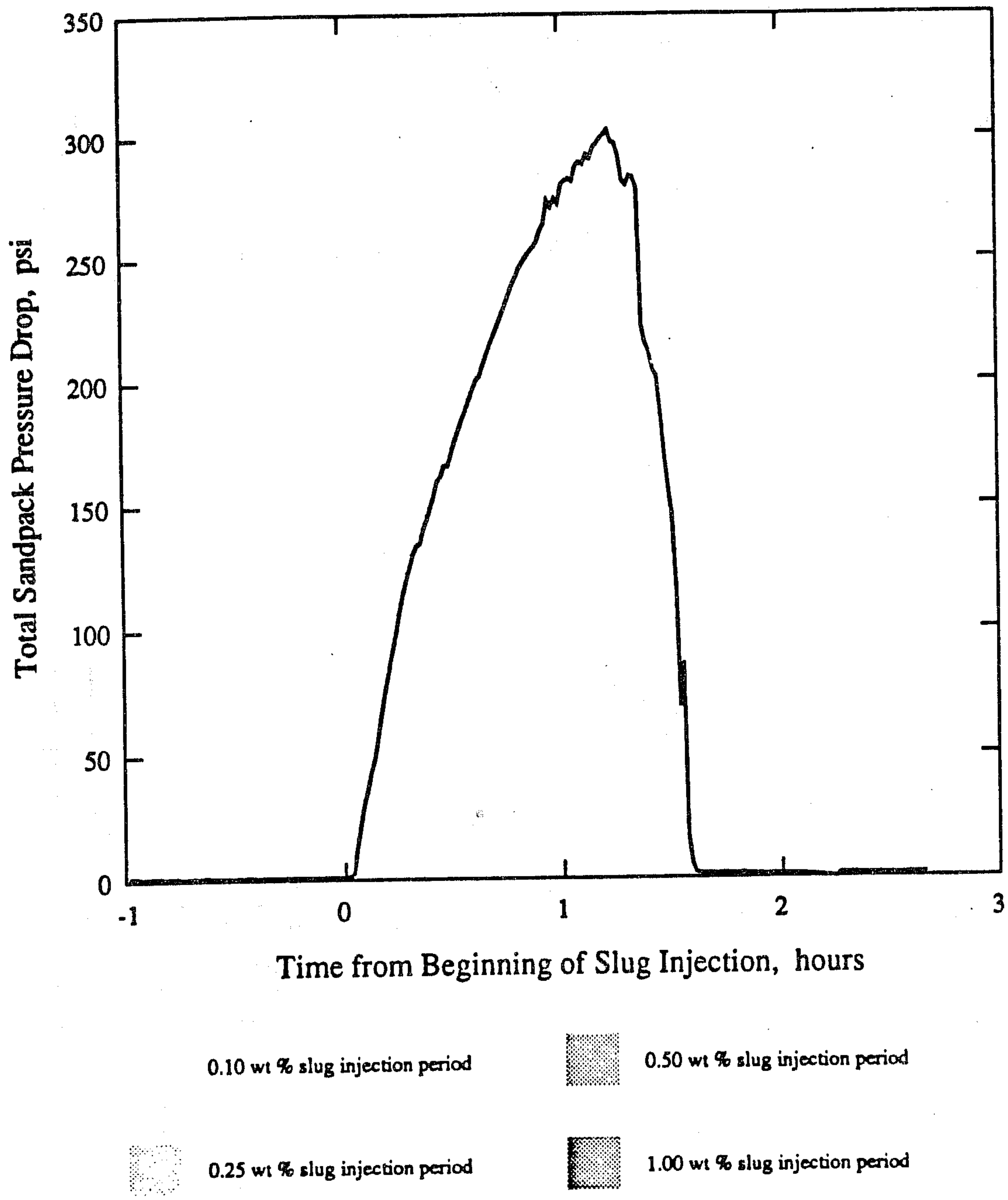

Figure 5.85 : Total Pressure Drop Response to Injection of One Slug of Shell Enordet AOS 1618 with Back Pressure at 40 psig - Run 32

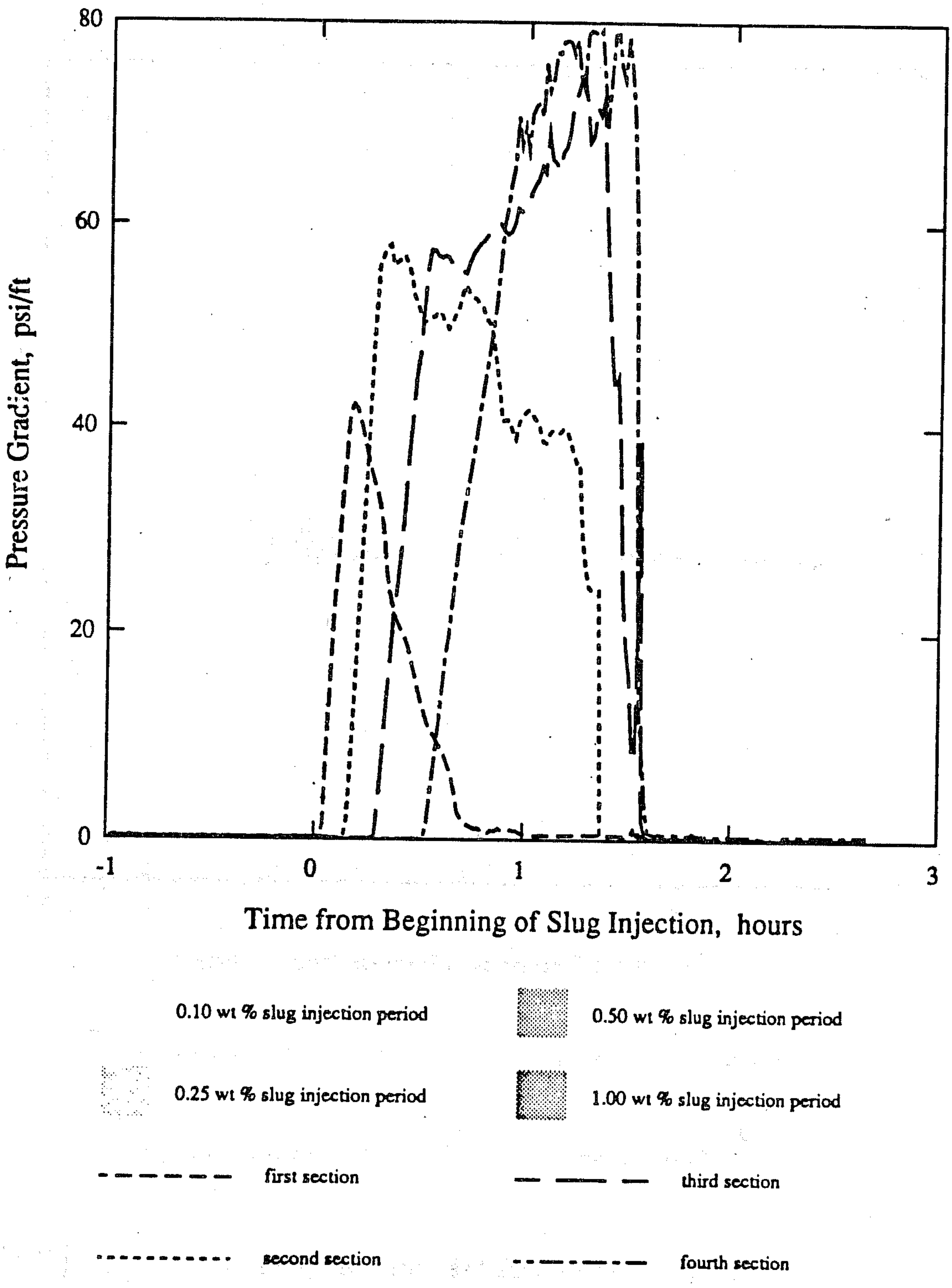

Figure 5.86 : Pressure Gradients within the Four Sandpack Sections in Response to Injection of One Slug of Shell Enordet AOS 1618 - Run 32

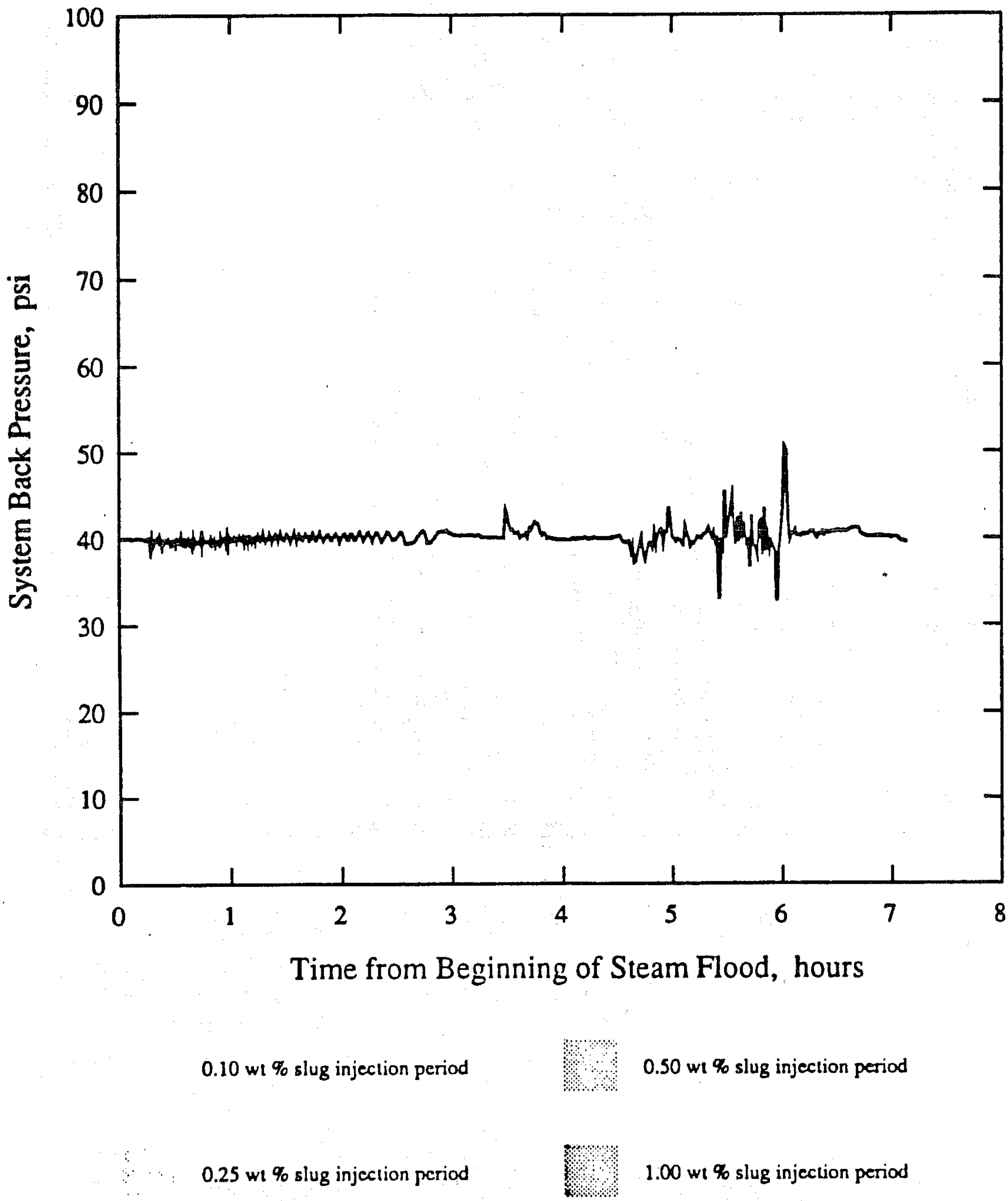

Figure 5.87 : System Back Pressure during Run 32

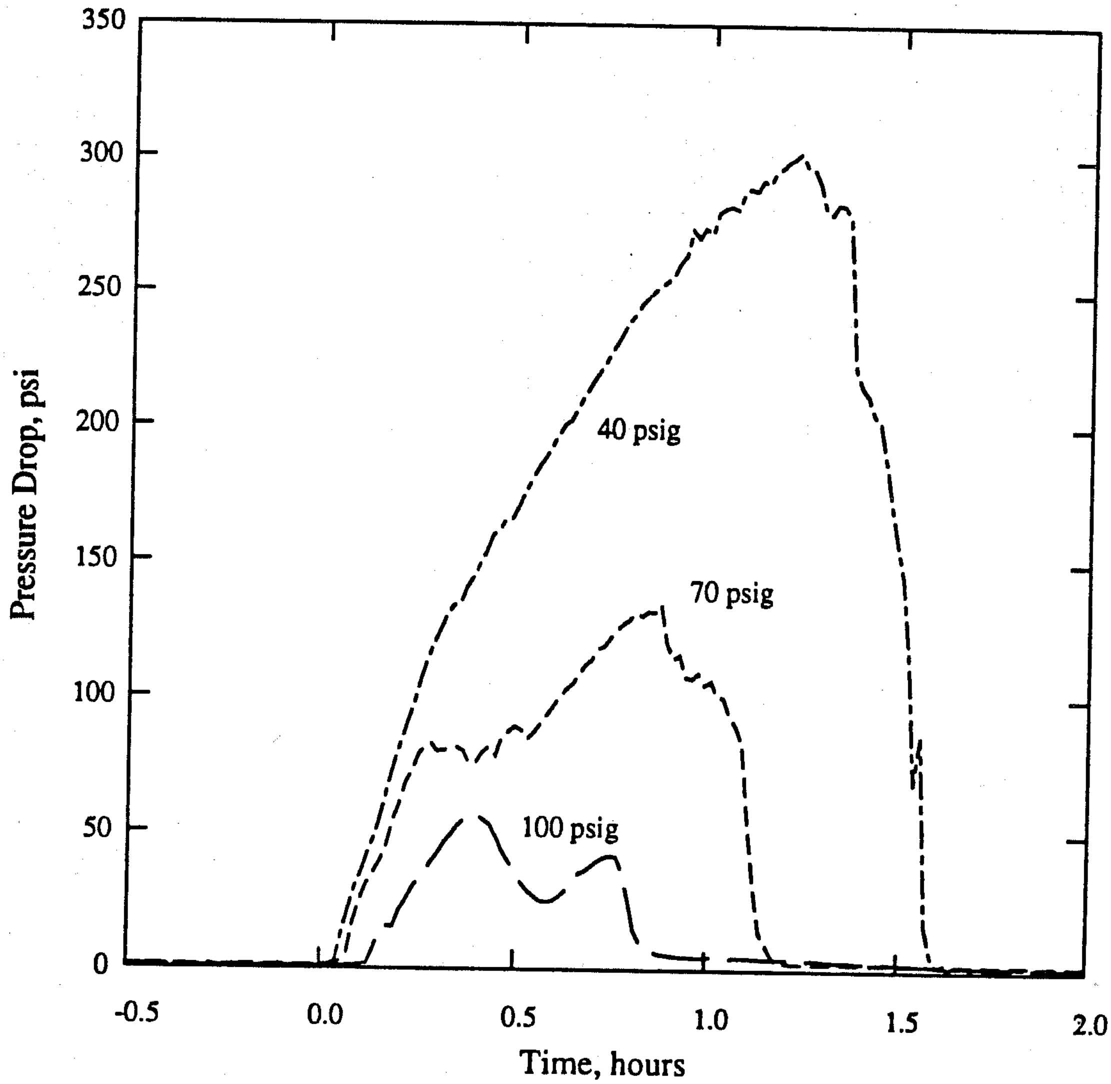

Figure 5.88 : Total Pressure Drop Responses to Injection of a 0.10 wt % Slug of Shell Enordet AOS 1618 at Three Different Back Pressures

maintaining a uniform back pressure from run to run if meaningful comparisons of pressure response data are to be made.

In considering why the pressure drop across the sandpack increases with decreasing back pressure the possibility that this observation may to some extent in some way be induced by the experimental technique must be considered. The stabilities of all the surfactants studied are susceptible to increase in temperature to some extent. The surfactant studied in this report are those that are known to produce stable foam at temperatures of at least 160°C. The half-life of the foam generated by the surfactants depends upon the temperature of the sandpack. Muijs *et al* (1988) showed for linear toluene sulphonate surfactants at least, that the pressure drop generated within a sandpack varies significantly with temperature. For a C_{18} LTS surfactant, at 180°C a pressure drop of about 175 psi is generated within the sandpack while at 225°C, only a 115 psi pressure drop is generated in the same pack. Consider the case when the system back pressure is set 40 psi. The steam saturation temperature at this pressure is 142°C. If, for example, the foam collapses at 210°C due to stability considerations then the maximum pressure that can be attained within the system is 277 psi, the steam saturation pressure at 210°C. Thus, the maximum pressure drop that can be generated within the system is 237 psi. Now suppose that the system back pressure is not 40 psig but 100 psi. The maximum pressure drop that can be generated within the system will be 177 psi, 60 psi less than the case for 40 psi back pressure. An analysis of the sandpack temperature data recorded during Runs 30, 31 and 32 suggests however however that the pressure drop generated within the system was not limited by the temperature tolerance of the foam.

6. DISCUSSION OF EXPERIMENTAL OBSERVATIONS

6.1. RANKING OF SURFACTANTS

Following the completion of the experimental programme the foam-forming abilities of the seventeen surfactants may be ranked based upon the magnitude and duration of the pressure responses. The major ranking criteria is the minimum concentration of the surfactant which resulted in the spontaneous generation of foam within the model. This is because in a field application it is desireable to minimize the quantity, and hence the cost, of the surfactant required. The surfactants are then ranked in descending order of the magnitude of the maximum pressure drop observed across the model in response to the injection of the first slug of the minimum foaming concentration. Where two runs were performed under similar conditions using the same surfactant the data used for ranking purposes is that relating to the run associated with the higher pressure drop. Finally, where two surfactants foamed at the same minimum concentration, and produced foam of similar strength, they are ranked according to the duration of the pressure response.

The foam-forming ability of seventeen surfactants are ranked in descending order in Table 6.1. The rankings are based upon the experiments performed with a steam saturation temperature of 156°C through a sandpack of clean, quartz sand in the absence of both oil and clays. Also, each surfactant solution contained 1.0 wt % sodium chloride.

Of the seventeen surfactants tested, four spontaneously generated foam within the sandpack in response to the injection of 0.10 wt % slugs, three foamed at 0.25 wt %, four foamed at 0.50 wt %, three foamed at 1.00 wt %, and three surfactants did not spontaneously generate foam at any concentration up to and including 1.00 wt %.

The highest-ranked surfactant tested was Shell's Enordet AOS 2024 which generated an exceptionally strong foam at just 0.10 wt %. Not only was the foam strong, but it persisted for 50 minutes after surfactant injection ceased. The foam was nearly twice as strong as the next best surfactant, Shell's Enordet AOS 1618. This slightly lighter alpha-olefin sulphonate has been successfully used to generate steam foam in the field as reported in Section 2.2. Chevron's Chaser SD 1000 may have only generated a relatively weak foam in response to the injection of te first slug, but it was one of only four surfactants which generated foam at 0.10 wt %. As a consequence, it is ranked fourth. Chaser SD 1000 is another surfactant that has been successfully used in the field as a foaming additive.

6.2. CHEMICAL STRUCTURE AND FOAM-FORMING ABILITY

Various workers have reported that the strength of the foam produced by a surfactant of a particular chemical structure, increases with increasing alkyl chain length. This observation is confirmed in the following sections.

6.2.1. The Alpha Olefin Sulphonates

The increases in pressure drops across the sandpack, observed in response to the injection of the first 0.10 wt % slugs of the three alpha olefin sulphonate surfactants are compared in Figure 6.1. This diagram clearly shows that both the strength of the foam and its persistence increases with increasing alkyl chain length. No increase in the pressure drop was observed in

Table 6.1 : Summary of Pressure Response data for the Seventeen Surfactants in Descending Order of Foam-Forming Ability

Surfactant	Manufacturer	Minimum Foaming Concentration (wt %)	Maximum Pressure Drop (psi)	Duration of Pressure Response (min)
Enordet AOS 2024	Shell	0.10	234	85
Enordet AOS 1618	Shell	0.10	132	68
Enordet LTS 18	Shell	0.10	58	> 120
Chaser SD 1000	Chevron	0.10	6	29
Enordet IOS 1720	Shell	0.25	217	79
Enordet IOS 2024	Shell	0.25	209	83
Hostapur OS fl	Hoechst	0.25	65	45
Hostapur SAS 60	Hoechst	0.50	> 215 †	76
Enordet IOS 1517	Shell	0.50	161	100
C 1416 AOS	Shell	0.50	71	> 118
Enordet LTS 1618D	Shell	0.50	42	> 206
Enordet LXS 18	Shell	1.00	246	> 85
Enordet LXS 16	Shell	1.00	230	87
Enordet LXS 1314	Shell	1.00	201	> 126
Enordet LXS 1112	Shell	Foaming did not occur at 1.00 wt %		
Enordet LXS 814	Shell	Foaming did not occur at 1.00 wt %		
Chaser SD 1020	Chevron	Foaming did not occur at 1.00 wt %		

† Pressure transducers overranged during slug injection.

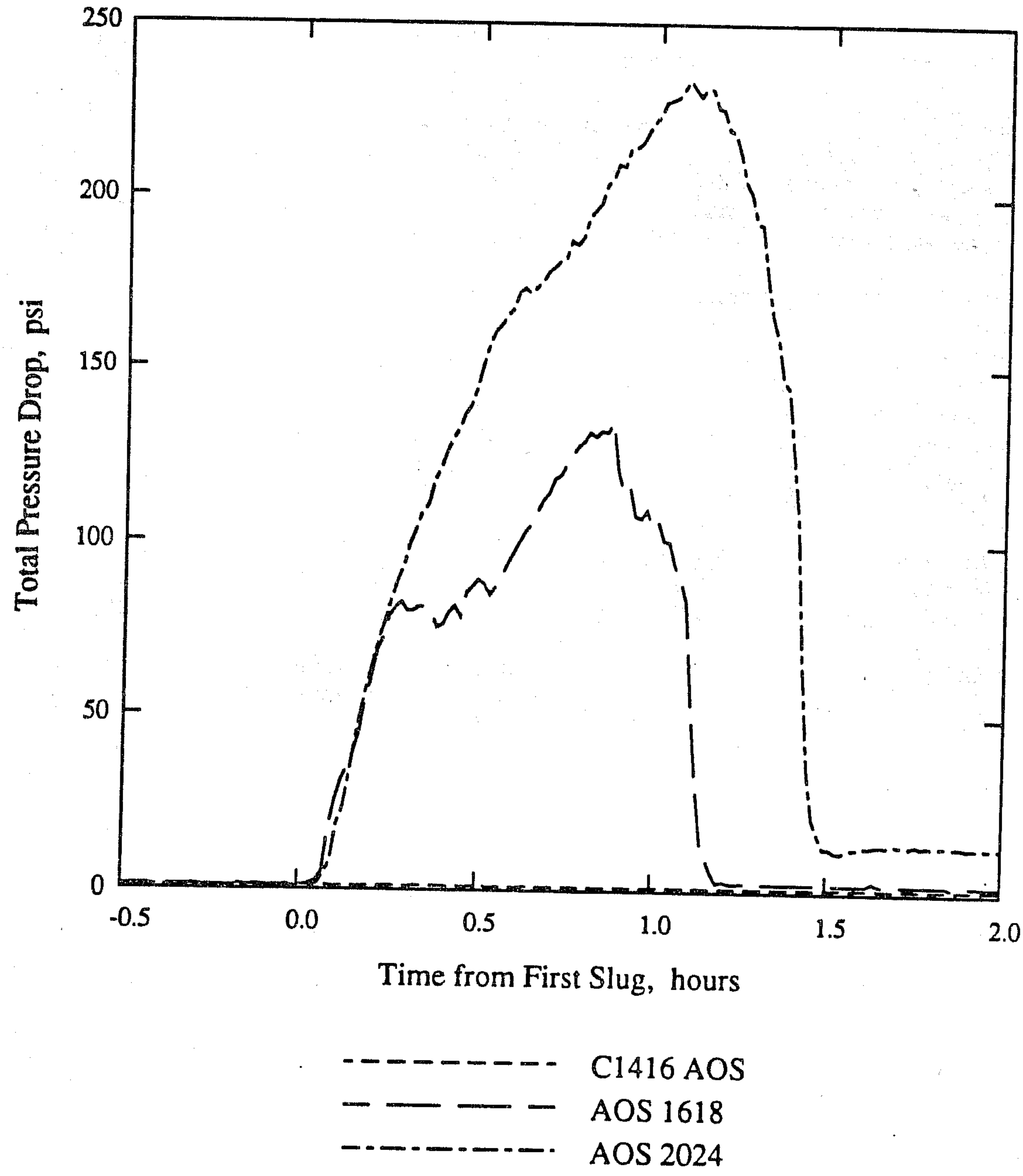

Figure 6.1 : Total Pressure Drop Responses to Injection of Single 0.10 wt % Slugs of the Alpha Olefin Sulphonates

response to the injection of the surfactant with the shortest alkyl chain, the C1416 AOS. The chemical structure of the AOS1618 only differs from that of the C1416 AOS by the addition of on average two carbon atoms to the alkyl chain, yet the injection of a 0.10 wt % slug of Enordet AOS 1618 spontaneously generated a strong foam. The Heavier AOS 2024 generated even stronger, more long-lived foam than the AOS 1618. On this basis, an AOS 2428 formulation could be predicted to produce a very strong foam.

6.2.2. The Internal Olefin Sulphonates

The three internal olefin sulphonates produced just as strong foam as the alpha olefin sulphonates, but only at higher concentrations. Figure 6.2 compares the pressure drops observed in response to the injection of the first 0.25 wt % slugs of the three internal olefin sulphonates studied. The lightest of these surfactants, IOS 1517, did not generate foam at 0.25 wt %. The two heavier surfactants both generated foams of similar strength and duration, but the response to IOS 2024 lagged about 16 minutes behind that of IOS 1720. This suggest that the IOS 2024 was absorbed and then desorbed in a process not fully understood by the authors.

6.2.3. The Linear Xylene Sulphonates

Five linear xylene sulphonate surfactants were tested during the present study and the pressure drops observed in response to the injection of the first 1.00 wt % slug of each of these surfactants are compared in Figure 6.3. The two prepartions of the lighter surfactants, LXS 814 and LXS1112, did not generate any foam within the sandpack following injection of 1.0 wt % concentration slugs. LXS 1314, the linear xylene sulphonate with 13 and 14 carbon atoms in the alkyl chain generated a maximum pressure drop of 201 psi. As with the internal olefin sulphonates, the two heaviest linear xylene sulphonate preparations produced foams of similar strength and duration, but the response to the heavier LXS 18 lagged about 55 minutes behind that of LXS 16. As before, a process involving absorption and desorption is suspected as being responsible for this lag time.

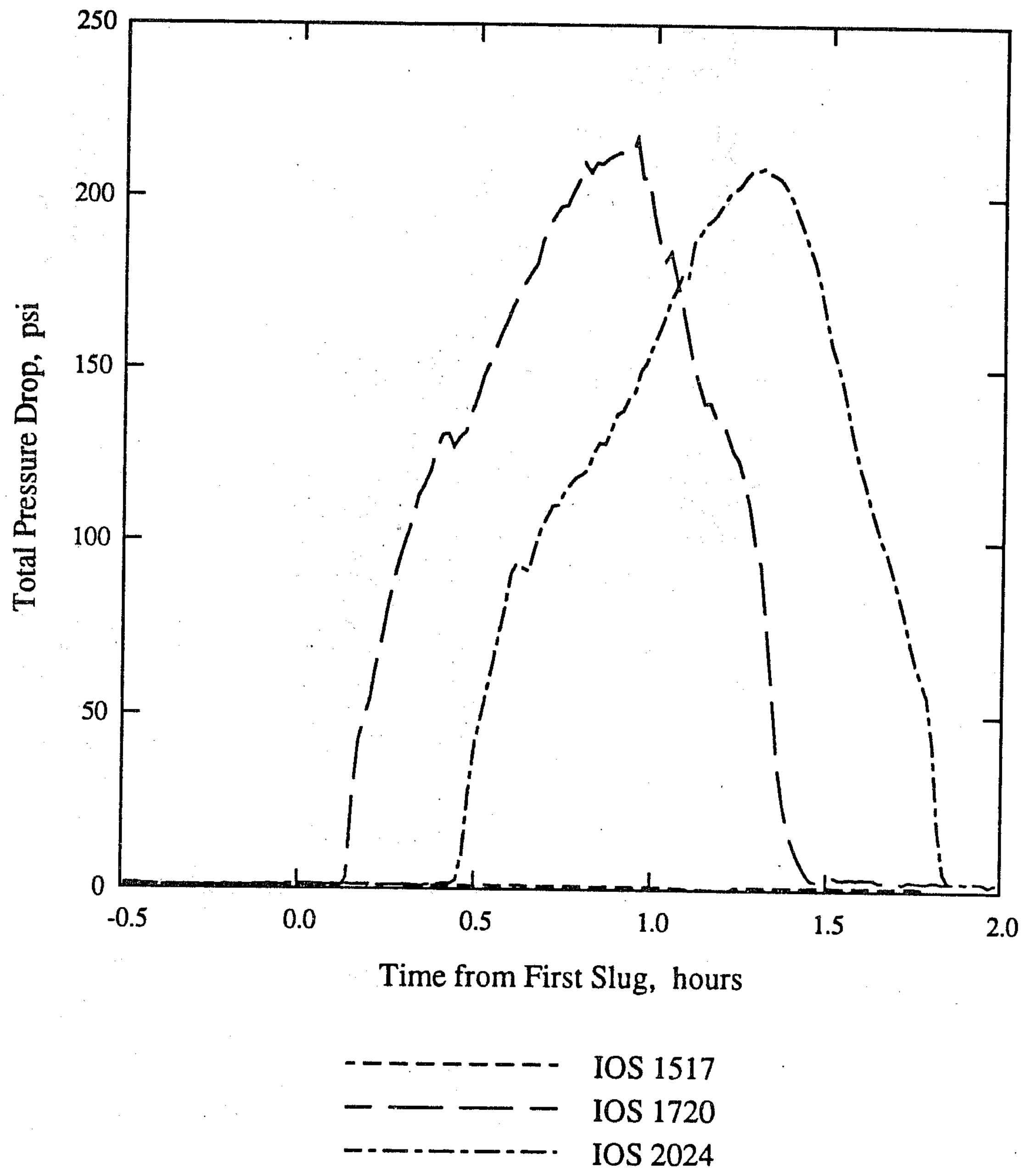

Figure 6.2 : Total Pressure Drop Responses to Injection of Single 0.25 wt % Slugs of the Internal Olefin Sulphonates

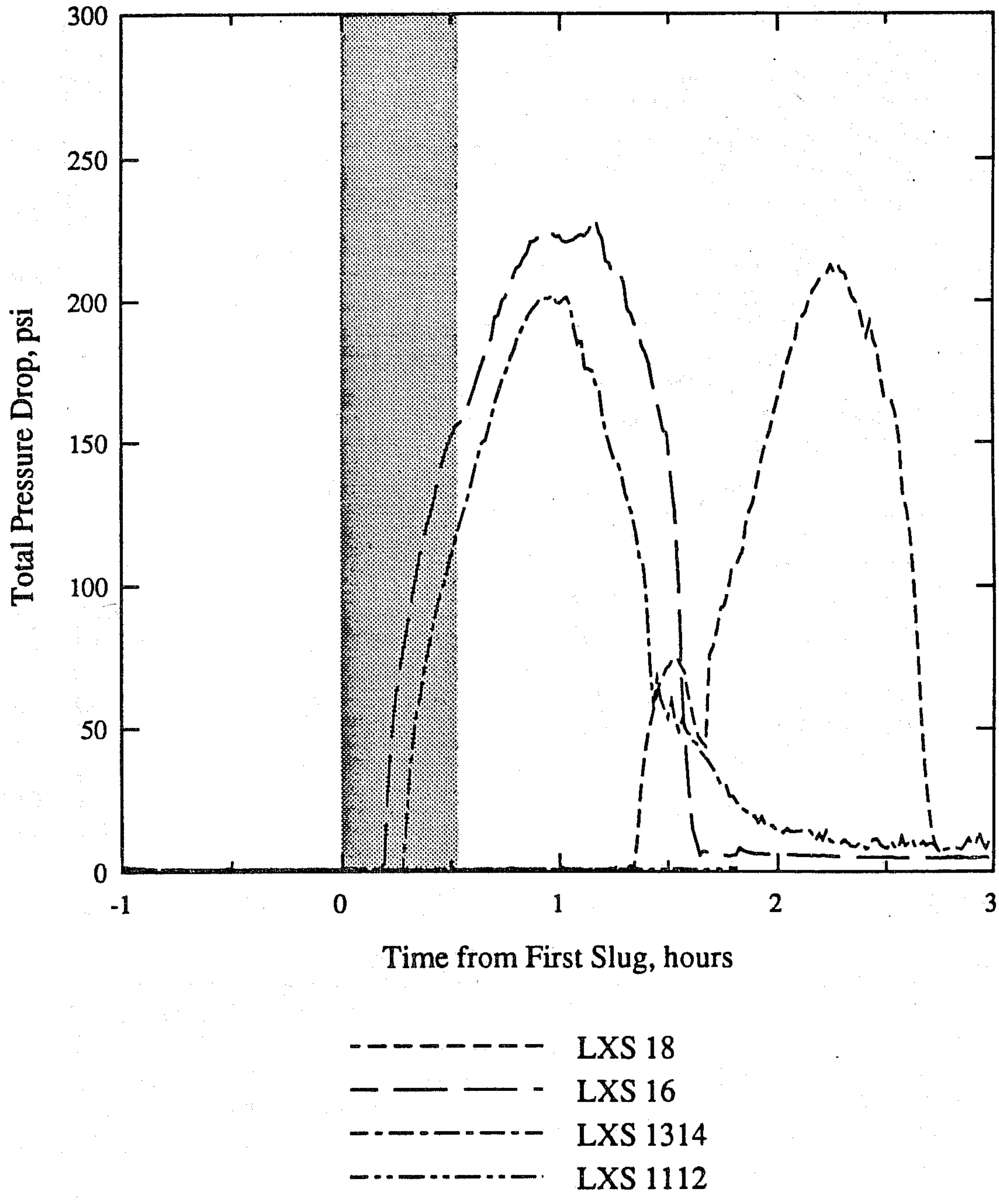

Figure 6.3 : Total Pressure Drop Responses to Injection of Single 1.0 wt % Slugs of Linear Alkyl-Xylene Sulphonate Surfactants

7. CONCLUDING REMARKS

7.1. CONCLUSIONS

The following conclusions may be drawn from this study:

- Under the experimental conditions alpha olefin sulphonate surfactants generate the strongest foams of all the surfactants tested at low concentrations.
- Internal olefin sulphonates and linear xylene sulphonate surfactants generate just as strong foams but only at higher surfactant concentrations.
- Shell's Enordet AOS 2024 generates a stronger, more long-lived foam than any surfactant used in the field to date.
- Under the experimental conditions, the strength of the foam produced by a surfactant of a particular chemical structure increases with increasing alkyl chain length. This was observed for alpha olefin sulphonates, internal olefin sulphonates and linear xylene sulphonates. Too few linear toluene sulphonate surfactants were studied to allow similar conclusions to be drawn.
- The presence of the non-condensible gas increased both the strength and duration of the foam formed.
- When non-condensible gas is present a gas foam forms, and advances ahead of the steam foam. Consequently, a significant proportion of the increased pressure drop observed across the sandpack is due to the presence of this gas foam rather than just the steam foam.
- Despite the presence of the insulation, the rate of heat lost from the model to the surroundings was significant. About half the injected steam was condensed due to heat losses before traversing the length of the sandpack.
- The rate of heat lost from the model varied significantly with time and location along the model during the generation and propagation of the foam.
- A thorough understanding of the heat transfer mechanisms existing within the system is necessary if the experimental observations are to be correctly interpreted. The heat flux sensors proved to be valuable tools in studying the heat transfer processes between the model and its surroundings.

7.2. RECOMMENDATIONS FOR FUTURE WORK

The results of this project provide a sound basis for further experimental programmes. Recommendations for future work to study the foam-forming ability of surfactants are:

- Reduce heat losses from the sandpack to the surroundings by either improving the insulation or placing the entire one-dimensional model in an oven.
- Study the effect of varying the fraction of non-condensible gas injected into the model. There may be some optimum flowrate.
- Perform a series of experiments using mixtures of clay and quartz sand, or natural reservoir sands as the porous medium to study retention and ion exchange of the surfactant.
- Using the four or five most promising surfactants perform a series of experiments using sandpacks containing oil at some residual saturation.

NOMENCLATURE

AOS	alpha olefin sulphonate
$\hat{H}$	specific enthalpy
IOS	internal olefin sulphonate
LTS	linear toluene sulphonate
LXS	linear xylene sulphonate
M	molecular weight
$\dot{m}$	mass flowrate
P	pressure
ΔP	pressure drop
Q	heat duty
R	universal gas constant
T	temperature
ρ	density

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