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International Agreement Report

RELAP5/MOD2 Analysis of LOFT Experiment L9-3

Prepared by
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RELAP5/MOD2 analysis of LOFT Experiment L9-3

J.C.Birchley

Abstract

An analysis has been performed of LOFT Experiment L9-3, a loss-of-feedwater anticipated transient without trip, in order to support the validation of RELAP5/MOD2.

Experiment L9-3 exhibited a rapid boildown of the steam generator, following the loss of feed, with the reactor remaining close to its initial power until the steam generator tubes became sufficiently uncovered for primary to secondary heat transfer to be significantly reduced. The ensuing heat up of the primary fluid resulted in a reduction in power induced by the moderator feedback. The primary system pressure increased to the safety relief valve setpoint, before the fall in reactor power allowed the mismatch between primary system heat input and heat removal via the steam generator to be accommodated by cycling of the pilot operated relief valve (PORV).

Comparison between calculation and data shows generally good agreement, though with discrepancies in some areas. Weaknesses in the code's treatment of interphase drag and in the representation of the pressuriser spray are indicated, although a shortage of definitive data, particularly in the steam generator, may also be a factor. The overprediction of interphase drag led to a tendency to underpredict the initial inventory in the steam generator and also, perhaps, to overpredict the steam generator heat transfer while the tubes were being uncovered. There is indication that the pressuriser vapour region conditions were close to equilibrium during spray operation. The point kinetics model in RELAP5/MOD2 proved a viable means of representing the power history for this transient.

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1. INTRODUCTION

The thermal-hydraulic computer code RELAP5 is to be used for the independent assessment of the Sizewell 'B' PWR with respect to design basis intact primary circuit faults and small break loss-of-coolant accients. In order to validate the RELAP5 code, a series of analyses of integral experiments is being performed using RELAP5/MOD2. This paper presents an analysis of LOFT Experiment L9-3, which was a simulated loss-of-feedwater anticipated transient without trip performed under the auspices of the USNRC. In this transient all feedwater was lost to the steam generator but the control rods fail to drop into the reactor core. The transient exhibited a number of features and phenomena that may occur following certain design basis accidents in Sizewell 'B', and which the code must be capable of representing. The phenomena of concern (Ref. 1) are:

- Decrease in SG heat transfer as secondary side boils down
- SG heat transfer during single phase forced circulation
- Pressure response during pressuriser insurge
- Mass and energy flows through relief valves
- Pressure response during operation of pressuriser spray

This report describes the RELAP5/MOD2 analysis of L9-3 and examines the code's ability to represent the phenomena listed above. The LOFT facility and its scaling relative to a commercial PWR are described in Section 2, and the conduct and course of Experiment L9-3 are described in Section 3. Sections 4 and 5 present the description of the RELAP5/MOD2 input model for the experiment and the calculations performed. The phenomena of interest are discussed in Section 6.

2. THE LOSS-OF-FLUID TEST (LOFT) FACILITY

The LOFT facility was a 50 MW (thermal) PWR (Fig. 1) designed to simulate the system response of a commercial PWR during loss-of-coolant accidents and intact primary circuit transients. The LOFT facility incorporated the major functional components of the primary and secondary systems of a commercial PWR, and instrumentation to measure the thermal-hydraulic and nuclear conditions in detail. The LOFT facility is described in detail in Reference 2.

2.1. Facility Description

The main features of LOFT are summarised as follows:

i. A reactor vessel with an annular downcomer, a lower plenum, an upper plenum, and a nuclear core with lower and upper support structure.

ii. An intact loop with an active steam generator, pressuriser, and two primary coolant pumps connected in parallel.

iii. A broken (passive) loop containing pipework with resistance and elevation changes designed to simulate the steam generator and pump, and two quick- opening blowdown valve assemblies (the steam generator and pump simulators were disconnected for experiment L9-3).

iv. A blowdown suppression system consisting of a header, suppression tank and a spray system. All fluid discharge from the primary coolant system was directed to the blowdown suppression tank. The blowdown suppression system was designed to simulate the pressure response of the containment during a loss-of-coolant accident and did not significantly affect experiment L9-3.

v. An emergency core coolant (ECC) injection system consisting of two low head injection system (LHIS) pumps, two high head injection system (HHIS) pumps, and two accumulators, and the associated pipework. The ECC system was not used in Experiment L9-3.

vi. A pressure relief line from the top of the pressuriser to the blowdown suppression tank, containing a relief valve with two open positions designed to represent the scaled discharge capacity of a power operated relief valve (PORV) in the first position, and the combined capacity of a PORV and a safety relief valve (SRV) in the second position, for a commercial PWR.

2.2. Scaling and Related Considerations

The LOFT facility was scaled to a commercial 4-loop PWR on the basis of power, volume, and flow. Not all of the components in LOFT were scaled by the same amount, however, and the elevation changes in LOFT were significantly less than the corresponding ones in a commercial PWR. For a transient such as L9-3, the features of the configuration for which scaling is most important are listed below, with the corresponding ratios:

Power ratio		68:1
Primary coolant system volume ratio		44:1
Pressuriser volume ratio		53:1
Pressuriser PORV and SRV relief capacity	approx	45:1

The LOFT facility is slightly oversized in comparison with the power scaling but not enough to alter the essential nature of the transient response. Other facility characteristics important for this transient are:

- Core reactivity
- Recirculation ratio in steam generator
- Steam generator elevation

The LOFT core is (naturally) smaller than a commercial PWR core, and as a consequence was subject to greater leakage of neutrons and larger radial peaking factors. A higher enrichment (4%) of U-235 was accordingly used in the LOFT fuel rods. The LOFT core was also irradiated for sufficient time only to establish required decay heat levels for each experiment, with the result that the burnup was roughly equivalent to an early stage of irradiation for a PWR. The combination of higher enrichment and low accumulated irradiation meant that the moderator void coeffient was representative of a commercial PWR core near the end of a cycle. In those circumstances the core is also in its least reactive (operating) state and the ATWT is less severe than it otherwise would be.

The steam generator characteristics of potentially most importance during a loss-of-feedwater transient are the recirculation ratio and height, since they have the biggest infuence on the changes in secondary side heat transfer conditions. The riser section is approximately one-third the height of a commercial PWR steam generator riser but the recirculation ratio is similar in magnitude to that in a commercial PWR. The transient thermal-hydraulic response (timing and rate of heat transfer degradation) will probably be somewhat different for LOFT and for a commercial PWR, but the governing processes are likely to be same.

The LOFT facility was subject to a number of scaling and other configurational distortions in the primary coolant system - e.g. elevation of the loop and core, presence of "dead" volumes in the broken loop. These are significant in small break LOCA transients and have a major influence on the phenomena occurring. They are much less important in an intact circuit fault transient such as L9-3, where issues such as liquid/vapour distribution, transition to natural circulation and counter-current flow did not arise.

A major difference between LOFT and a commercial plant is in the height of the pressuriser. The LOFT pressuriser was approximately one-seventh the height of a commercial PWR pressuriser, so that the interface between the liquid and vapour regions (and hence any thermal-hydraulic coupling between them), and also the potential for liquid insurging into the pressuriser to mix, are more important in L9-3.

From the above considerations, it is concluded that the L9-3 data are suitable for code validation in respect of the phenomena identified in section 1, with the provisos that the pressuriser dynamics need to be carefully examined and that L9-3 is relevant only to symmetric loss-of- feedwater transients.

3. DESCRIPTION OF EXPERIMENT L9-3

Experiment L9-3, which was performed on 7 April 1982, simulated a loss-of- feedwater accident without reactor trip and was the first of two ATWT experiments performed in LOFT. The test is described in detail in references 3 and 4. A brief description is given below.

3.1. Objectives of Experiment L9-3

The programmatic objectives of Experiment L9-3 were to:

i. Provide experimental data for benchmarking PWR vendor's ATWT computer codes as required by the NRC proposed ATWT rule (USNRC-SECY-80-409).

ii. Evaluate alternative methods of achieving long-term shutdown (without the insertion of control rods) during an ATWT event, to address concerns defined in the proposed staff rule (Federal Register Vol. 46, No. 226).

3.2. Conduct of Experiment L9-3

The experiment was performed in two phases. For the first 600 secs of the transient only automatic plant protection systems were simulated. This phase corresponds to the period of 10 minutes during which time the automatic systems are required, in U.S. practice, to maintain the plant in a safe condition, with no credit taken for operator intervention. This first phase provided the data relevant to code validation (corresponding to the first programmatic objective), and is the portion of the experiment analysed in the present study.

The initial conditions for Experiment L9-3 are listed in Table 1, and were representative of nominal PWR operating conditions. The experiment was initiated by terminating all feedwater delivery to the steam generator. The following conditions applied during the transient:

- All reactor trip setpoints (low steam generator liquid level, high pressure or temperature in the hot leg of the primary coolant system, etc.) were inactivated, and the transient was allowed to proceed for 10 minutes with no operator intervention.
- The pressuriser spray, PORV and SRV were operated according to primary coolant system pressure setpoints.
- The main steam control valve was closed when the steam generator had boiled partially dry (as indicated by a high primary pressure reading).
- The main steam bypass valve was cycled on high steam generator pressure to simulate the action of the steam generator safety relief valves.
- The primary coolant pumps continued to be operated.

At the end of this period, the reactor operators initiated a controlled recovery which consisted of primary system feed (with highly borated liquid) and bleed, and secondary system cooldown (via cycling of the feedwater supply). The control rods remained in the normal full power position during the ATWT and recovery phases of the transient.

3.3. Summary of Transient

The sequence of events is described briefly as follows:

After turning off the main feedwater pump, the feed flow started to decrease from its initial value. This was designated as the reference time zero. The primary to secondary heat transfer degraded slightly almost immediately due to the loss of subcooling of the secondary coolant, induced by the loss of feedwater. This caused the primary coolant temperatures and the secondary side pressure to increase slowly during the first 50 seconds of the transient.

The rise in primary coolant temperature caused the fluid to expand and there was a slow insurge into the pressuriser, with a consequent rise in primary system pressure. This caused the pressuriser spray to begin cycling at 30 s.

The secondary side coolant continued to boil off with the result that the tubes started to uncover at about 30 s. The primary to secondary heat transfer then began to degrade more rapidly, such that the primary coolant temperature increase, and the insurge to the pressuriser, resulted in a pressure rise that exceeded the capacity of the pressuriser spray to control. At 74 s the pressuriser PORV opened.

As the steam generator boiled dry, the initial increase in secondary side pressure was reversed, as insufficient steam was now being generated to maintain pressure. The main steam control valve was closed at 67.3 s, with the steam generator liquid level slightly above the bottom of the indicating range and the tubes substantially uncovered. Following closure of the control valve, the secondary pressure increased again to the steam bypass valve setpoint. The small amount of continuing steam generation was then balanced by the bypass flow during two cycles of valve opening and by the leakage of steam through the main steam control valve.

The pressuriser liquid level meanwhile continued to rise and reached the top of the indicating range at 90 s. The subsequent increase in discharge fluid density resulted in a PORV volumetric flow that was less than the primary coolant rate of expansion. This mismatch caused the primary system pressure to increase again, reaching the SRV setpoint at 107 s, after which the combined SRV and PORV capacities were sufficient to maintain the pressure at or below the SRV setpoint.

The increase in primary coolant temperature also reduced the reactor power via the feedback on the moderator temperature and density. As a result, the primary coolant heat source/heat sink imbalance reduced to the extent that after the SRV had cycled once, the PORV alone was sufficient to to control the system pressure. The transient continued with the PORV cycling and reactor power decreasing until an approximate balance was achieved between the primary heat source and sink at about 200 s, after which cycling of the PORV ceased. During the following 400 s, the primary pressure and temperature remained approximately constant, at 15.7 MPa and 595 K, repectively.

At 600 s, the reactor operators initiated a controlled recovery by (a) starting injection of 7000 ppm borated water into the primary coolant system from the high head injection system, (b) starting injection of feedwater to the steam generator, and (c) latching open the PORV. This operation successfully recovered the plant and returned the intact loop hot leg temperature to 583 K at 1080 s. This recovery phase of the experiment is not analysed in the present study. The significant events monitored during the transient are detailed in Table 2.

4. RELAP5/MOD2 MODEL OF THE LOFT FACILITY

The code version used for the analysis of Experiment L9-3 was RELAP5/MOD2 Cycle 36.05 UK Version E03. The code is described in references 5 and 6; UK modifications incorporated into Version E03 are summarised in the output from running the code version.

The input model (Ref 7) was based on that previously used by CEGB GDCD for analysis of LOFT loss-of-feed Experiment LP-FW-1 (Ref 8) and loss of on- and off-site power ATWT Experiment L9-4 (Ref 9). The noding diagram for the calculations is shown in figure 2. The following experiment features were included in the input model:

i. The pumps were kept running throughout the transient.

ii. The pressuriser spray was operated.

iii. The experimental pressuriser relief valve assembly was designed to operate in two positions, to represent the relief capacity of a single PORV, and of a PORV and SRV combined. This was represented in the input model by a SRV and PORV which were modelled as trip valves that would be either fully open or fully closed in relation to the setpoints. The flow areas of the PORV and SRV were specified to provide steam flows of 0.66 kg/s at a pressure of 16.2 MPa with the experimental relief valve in the first (PORV) position, and a flow of 1.52 kg/s at a pressure of 17.2 MPa in the second position.

iv. The auxiliary feedwater was disabled.

v. The steam generator and pump simulators were replaced by a blind flange in Experiment L9-3. The nodes representing the simulators and the pipework downstream thereof were deleted in the input model used for the analysis.

vi. As stated in section 2.2 the LOFT core moderator feedback characteristics were typical of a commercial PWR at end-of-life conditions. The moderator void and temperature reactivity data provided in the RELAP5 deck for LOFT had been specified on the basis of core physics calculations performed at INEL to support safety analysis of LOFT experiments and had been used in their own post-test analysis of L9-3. In order to confirm that the data given are in fact representative of end-of-life conditions, they were compared with the predicted reactivity obtained by core physics calculations for Sizewell 'B' (Ref. 6). From Figure 3, it can be seen that the LOFT model data are at least comparable with the Sizewell prediction at zero loading of boron. The reactivity data were used in conjunction with the RELAP5/MOD2 point kinetics model instead of specifying the power as a function of time. This provides representation of the power reduction as driven by the moderator feedback, and ensures that the power transient is consistent with the thermal-hydraulic transient.

vii. Decay heat was calculated by by the code's default decay heat model, which employs the ANS 1973 decay heat data, together with a user specified multiplier (in this case, unity) reflecting best estimate or consevative decay heat levels. Inspection of the calculated decay heat levels shows fair agreement with those quoted in the L9-3 data report, bearing in mind that the quoted levels are based on an assumption of scram occurring at 400 s.

5. RELAP5/MOD2 CALCULATIONS OF LOFT EXPERIMENT L9-3

This section describes two calculations for L9-3. The first calculation employed the same input deck as was used in the analysis of L9-4, with the changes described above. The second calculation was performed using an input deck with a number of further changes designed to simulate the experiment more closely.

5.1. Initial Conditions

Prior to performing the transient calculation, a steady state calculation was performed in which the RELAP5 control logic was used to adjust the pump speed, feedwater flow, secondary pressure, steam generator level, and primary system pressure. A short null transient calculation was then carried out to confirm that the steady state was fully converged. The initial conditions obtained at the end of the null transient are compared with the experiment initial conditions in Table 1. Agreement is seen to be satisfactory bearing in mind that there is some uncertainty in the data for the liquid and vapour volumes in the pressuriser. The calculation sought to match the latest information from INEL for the pressuriser dimensions.

5.2. Transient Calculations

5.2.1. Preliminary Calculation

The first calculation was performed with the RELAP5 input model unchanged from the form used for the analysis of LOFT Experiment L9-4 performed by CEGB Barnwood. The only changes made to the input were those corresponding to the initial and boundary conditions for Experiment L9-3. The objectives in performing an initial calculation with an unchanged model were:

- to assess the degree to which the input model used previously is uniformly applicable over a range of conditions.
- to provide a baseline calculation from which improvements or sensitivity calculations can be made.

It was decided to run the initial calculation, at least at first, for just the early part of the transient in order to make a preliminary asssessment of the model. Figures 4, 5 and 6 compare the experimental and calculated primary system pressure, the cold leg and hot leg temperatures, and the pressuriser liquid level. The effect of the loss-of-feedwater is first indicated in the primary system after about 5s, as the loop temperatures and pressure begin to rise. The calculation follows the experiment data quite well during the early stages, to about 40 s, although the initial increase in temperature is slightly more marked in the calculation. The calculated pressure transient first deviates from the data at 24 s, when the pressuriser spray flow was initiated prematurely in the calculation, as the spray set point was specified according to the experiment specification, whereas the spray did not begin until the pressure had risen by a further 0.1 MPa. In the experiment the pressure then fell rapidly, such that the spray tripped off a few seconds later, to be followed by two further cycles of spray initiation. The calculation exhibited only a gradual reduction in pressure, with the result that the spray flow continued for the remainder of the transient. This contrast between calculation and data has been reported in many RELAP5 analyses of LOFT transients, for example reference 8.

The discrepancy between calculation and data for the primary system pressure following spray initiation tends to mask the comparison generally. As can be seen from figure 5, the coolant temperatures continue to remain in good agreement until the boildown of the steam generator leads to a general degradation in primary to secondary heat transfer. Since the pumps were running throughout the transient, the heat transfer is essentially controlled by the secondary side conditions, rather than the primary and secondary sides as it was in L9-4. A second rise in coolant temperatures began at about 50 s, with a steady increase in the rise rate as the steam generator tubes became progressively uncovered. The onset of the degradation was slightly delayed in the calculation, but once initiated the primary coolant temperatures increased more rapidly than in the experiment. The hot leg temperature increase was less dramatic than in the cold leg, since the power reduction induced by the moderator feedback led to a smaller rise in temperature across the core. The pressuriser level provides an indication of the average coolant temperature in the primary system. As can be seen from figure 6, the level increases more sharply in the calculation than in the experiment, but at the time the (measured) level was at the top of the indicating range, the they were almost coincident. This appears to be at variance with both the coolant temperatures in the loops and and system pressure. There may be processes occurring in the pressuriser that are not adequately modelled (such as the effect of spray flow).

The calculated and measured powers are compared in figure 7. The calculated power fell slightly more just after the start of the transient, reflecting the slightly more pronounced early temperature increase. The nature of the later power transients also reflects the respective coolant temperature histories. It is worth noting that the total heat generation in the core during the first 100 s was less in the calculation than in the experiment, but the calculated coolant temperatures rose by a greater amount. Therefore the total heat transferred to the secondary side was less in the calculation than in the experiment. The reason(s) for this may be either too little initial inventory in the steam generator or a degradation in heat transfer at too high a remaining inventory. This will be examined in the analysis of the secondary side conditions, to follow.

In order to check the modelling of reactivity, the reactor power is plotted in figure 8 against coolant temperature in the cold leg, for both the calculation and data. Because of the difference in temperature histories, exact agreement could not occur, even if the neutronics were repesented exactly. The closeness of the curves, however indicates that the reactivity was modelled adequately for the purpose of this study, at least.

Attention is turned now to the conditions in the steam generator, in order to understand the factors that caused the observed primary coolant system transient, and to explain some of the differences between the calculation and data. The secondary pressure history is shown in figure 9. Following the loss-of-feedwater, the pressure increased gradually (after a short delay corresponding to the time over which the feed flow terminated and the transit time between the injection point and the boiler.) The pressure increased as subcooling was lost from the liquid entering the bottom of the boiler. As a result, rather more steam was generated for the same quantity of heat transferred across the tubes. The secondary pressure then began to restabilise at a slightly higher value, and with a steam generation rate and flow also slightly higher. The initial increase in pressure was slightly more marked in the calculation, and this led to the correspondingly more marked initial increase in primary coolant temperatures. There was no apparent degradation in heat transfer until about 50 s, at which time the pressure began to fall as the rate of steam generation dropped.

At 67.3 s the main steam control valve began to close. Further steam generation then caused the pressure to rise once again until the steam bypass valve was manually operated to limit the pressure. The calculated fall in pressure occurred a few seconds later than shown by the data, but was much more dramatic, as if steam generation suddenly ceased. In the calculation the pressure fell to 2.5 MPa compared with 4.5 MPa in the experiment.

Figure 10 shows the steam generator downcomer collapsed level, for which there was excellent agreement between calculation and data for the first 30 s. From then until the MSCV was closed the calculated level decreased more rapidly than the measured level, suggesting there may have been too small a flow area within either the downcomer or boiler, and hence too small an initial inventory in the calculation. In the experiment the level was just above the bottom of the indicating range at 67.3 s, whereas the steam generator was almost empty in the calculation. From this we may deduce that either of both the following states applied:

i. the calculated initial inventory was too small.

ii. good heat transfer was maintained in the calculation at inventories below that at which degradation occurred in the experiment.

These deductions are confirmed by figures 11, and 12, which compare the calculated and experimental steam flow, and primary to secondary heat transfer, respectively. As can be seen, the integrated steam flow is less in the calculation, despite the fact that there was less liquid remaining in the steam generator when the MSCV was closed. The plot of heat transfer as a function of steam generator level, figure 13, shows even more clearly that the calculated heat transfer remained almost unchanged during the boildown until the steam generator was almost empty.

5.2.2. Revised Calculation

In order to try to resolve the discrepancies between calculation and data, and determine whether they were due to weaknesses in the code or in the input model, a number of changes were made to the input model as follows:

i. The bottom node in the boiler and downcomer of the steam generator were subdivided into two, to seek a more gradual degradation in heat transfer.

ii. The flow area in the lower part of the steam generator downcomer was increased in line with engineering data on the LOFT facility (Ref 10).

iii. The flow resistance of the steam generator was reduced to increase the circulation ratio. (This and the previous change were intended to increase the initial inventory in the steam generator.)

iv. Adjustment of the trip settings to match more closely the measured conditions at actuation.

The calculation was run to 600 s. The revised model gave results that are qualitatively similar to the original model, but with the steam generator boiling dry slightly later. The primary system pressure history calculated using both models is compared with the data in figure 14. The revised calculation is compared with data for the period to 600 s in figure 15. The effect of slightly higher pressure for spray initiation, and the higher initial steam generator liquid inventory results in slightly better timings for key events, but the general course of the transient is not significantly changed. Surprisingly, the rapidity of the pressure increase as the steam generator boils dry is not changed. The comparisons for the hot and cold leg fluid temperatures show a shift in time by a few seconds, reflecting the higher steam generator inventory. These quantities are shown in figure 16. The shape of the power history is essentially the same as in the previous calculation. However, there is a temporary decrease in primary coolant temperature at about the time of MSCV closure that caused a slight increase in power, but the total power generated is closer to the experiment, as shown by figure 17.

Although the calculated pressure rise after about 60 s is still too rapid, and the timings for initiation of PORV and SRV cycling consequently too early, it is useful to compare the calculated and measured pressure histories for the remainder of the transient. The calculation constrasted with the data in that (i) the SRV was calculated to open before the pressuriser had filled with liquid, (ii) the pressure transient was brought under control (by PORV cycling) considerably later than it was in the experiment. Cycling of the PORV between the open and close setpoints maintained pressure between those points, as occurred in the experiment but with much longer duration.

The steam generator pressure and level are compared in figure 18 and 19, respectively. The revised pressure history is in better agreement, mainly because the pressure had not fallen so far, and slightly more liquid was remaining, at the time of MSCV closure. One of the changes to the model was that the MSCV was closed at the same pressure as obtained in the experiment. The time of closure, however, was almost identical, apparently because the total heat transferred, and hence steam generated up to this point, were in close agreement with experiment. This is confirmed by figure 20, which compares calculated and measured steam flows. However, the steam generator pressure did not rise to the steam bypass setpoint in the calculation, so there was no bypass flow calculated.

Agreement for primary to secondary heat transfer, shown in figure 21, was not greatly different, apart from the later onset of heat transfer degradation. The finer noding at the bottom of the steam generator was expected to result in smoother degradation in heat transfer as the tubes uncovered. Instead, the heat transfer was more unstable, possibly because there was more liquid remaining when the MSCV was closed.

6. DISCUSSION

The transient calculation is now discussed in general, and in respect of particular aspects of interest.

6.1. General

The RELAP5/MOD2 calculation gave a reasonable simulation of the experiment, though with some discrepancy for particular aspects of the transient. The first 60 s were well predicted, except for the sharp drop in pressure following spray initiation. The most important factor controlling the transient is the primary to secondary heat transfer during boildown of the steam generator. This affects the balance (or imbalance) between primary system heat input and removal which, in turn, dictates the primary coolant temperature transient, the pressure transient, and the timings for PORV and SRV opening and closing. In particular the calculated steam generator heat transfer was only about ten percent of the decay heat level. The actual heat transfer is difficult to quantify from the data, but there is indication (e.g. figure 21) that it was being underpredicted in the calculation.

The moderator driven power reduction eventually restored the primary system heat balance. The balance was reached somewhat later in the calculation than in the experiment, but both exhibited a period in which the pressure was controlled by cycling of the PORV. Subsequently losses to the environment and metalwork, and steam flow through the (leaking) MSCV were sufficient to remove the decay heat with the PORV closed. During this period slow changes in primary pressure occurred as the relative magnitudes of these factors varied. The calculation did not match the data exactly during this last stage of the transient, but the differences are probably explainable in terms of uncertainty in steam leakage and in the amount of liquid remaining in the secondary side after cycling of the bypass valve.

A consequence of the differences between calculation and data is that the timings of key events, and their order are different. This is more apparent in Experiment L9-3 than it was in L9-4 because of the greater number of events happening within a short space of time. The timing of the events influenced the boundary conditions (e.g. spray flow), so that comparison of the code via comparison of the pressure trace is complicated.

6.2. Primary to secondary heat transfer

The most significant discrepancy between calculation and data was the rate at which the primary to secondary heat transfer degraded as the steam generator boiled dry. The calculation exhibited an undiminished heat transfer until the boildown was almost complete, whereupon there was a sudden drop in heat transfer, and a consequent increase in primary system pressure. The heat transfer history is affected by two factors: (i) the relation between heat transfer and remaining inventory, (ii) the initial inventory.

Comparison between the first calculation and the data shows the primary to secondary heat transfer to fall prematurely as well as too sharply. Inspection of the steam flow confirms that the initial inventory must have been too small by at least 100 kg (about five percent) and very probably more. The main factors that affect the initial inventory are (i) the configuration of the steam generator, (ii) the recirculation ratio, (iii) the interphase drag, and (iv) the subcooled void. The effect of changes made to the input model to increase the inventory are shown in figure 20, which shows the total steam flow up to the time of MSCV closure to be close to experiment. The initial inventory was probably still too small since comparison of the level indicate an underestimate of liquid remaining at the time of MSCV closure. Since the changes made were as large as was thought to be sensible, there remains the likelihood that shortcomings in the interphase drag and subcooled void models resulted in too high a void fraction initially in the riser.

The sudden nature of the drop in steam generator heat transfer was thought to be due to use of too coarse a nodalisation. The smearing of the liquid over each fluid cell means that too large an area of the tubes remains wetted until the fluid conditions change to those corresponding to dryout. Subdividing the nodes at the bottom of the steam generator was expected to reduce this effect. However the behaviour proved to be essentially as before. Figures 22 and 23 show the calculated liquid fraction and heat transfer in each node in the riser. Prior to closure of the MSCV, the liquid fractions decreased more or less together, so that instead of showing a sequential emptying, the liquid was still smeared to a large extent. As a result the heat transfer remained high in all the nodes until they were all nearly empty, whereupon the heat transfer fell sharply in all of them. This appears to be attributable to an overestimate of interphase drag, so that liquid is carried up into the higher nodes.

The heat transfer fluctuated considerably during the later stages of the boildown. This was due, in part, to the redistribution of a quantity of liquid in the downcomer at the time of MSCV closure, temporarily increasing the amount of liquid in the riser, and in part to the tendency of the code to predict large changes in local heat transfer as a fluid cell empties.

6.3. Pressuriser reponse

An additional discrepancy is the rate at which the primary pressure increased as the pressuriser filled. For a given level increase, RELAP5/MOD2 calculated a pressure that was greater than shown by the experiment data. A contributing factor is the underprediction of the heat removed from the vapour by the spray. In order to assess the possible magnitude of this effect, a further sensitivity calculation, not to be regarded as a best estimate, was performed in which the pressuriser was assumed to be in equilibrium from the time at which the spray flow was initiated. This assumption maximises the heat transferred from the vapour to the liquid, and should certainly overstate it, in fact. The resulting pressuriser level and pressure transients are shown in figures 24, 25 and 26.

Prior to spray flow the rise in pressure with level is accurately calculated, Following spray actuation, there is a drop in pressure not effectively simulated, followed by a rise with level with a lesser gradient than before. Invoking equilibrium in the pressuriser at the initiation of spray flow gave improvement in the relationship between level and pressure, and a closer agreement in gradient. However, the initial decrease in pressure was still too small, and there is the possibility that the liquid in the spray line was much cooler than the cold leg temperature assumed in the calculations. The effect of initial spray line temperature would last for only a few seconds of spray flow, however.

6.4. Mass and energy flows through relief valves

Assessment of the representation of mass and energy flows through the PORV and SRV is complicated because the fluid conditions in the relief line differed between experiment and calculation. The relief line flow and pressure are shown in figures 27 and 28. (A further sensitivity case in which the subcooled discharge coefficient for the PORV was increased from 1.0 to 1.8 (specifically to seek agreement with data) is displayed.) Prior to filling of the pressuriser the calculated flow rate through the PORV and SRV agreed with the specified flow for steam and with the data for the PORV flow. In the calculation the SRV opened once before the pressuriser filled, and again afterwards, whereas the SRV opened only after the pressuriser filled in the experiment.

The underestimate of the PORV flow when liquid was being discharged affected the remainder of the pressure transient, as was reflected in the extra time before the pressure was brought down to the PORV closing setpoint. The calculation with the subcooled discharge coefficient for the PORV increased to 1.8 gave (as expected) good agreement for the flow and the ensuing pressure transient. In particular, the period during which the SRV remained open, and the time of initiation of PORV cycling was closely matched. This calculation, like the previous one with equilibrium assumed in the pressuriser is intended mainly as a sensitivity, rather than a true best estimate. However, the discharge characteristics may, in fact, be known with more certainty for plant studies than for LOFT.

6.5. Shortage of experiment data

A shortcoming of the LOFT facility is the paucity of instrumentation in the steam generator. Data are not available for void distribution, mixture level, or tube temperatures in the riser, and the initial inventory and recirculation ratio is not known exactly. This makes assessment of the two fluid modelling in RELAP5/MOD2 less clear.

6.6. Code problems

The following problems with the code are noted.

i. The onset of carryunder results in a surge of two-phase fluid from the downcomer to the steam dome, and an increase in vapour generation. In all the calculations here, attempt was made to suppress this by reducing the value of VUNDER such that carryunder did not occur until the steam generator was almost totally void.

ii. The use or the MTRVLV type for PORV and spray valve actuation can cause the valve to open only partially when the setpoint is reached. This may have affected the preliminary and revised calculations in which, on close inspection, it was found that only a fraction of the full spray was occurring for a considerable time. This did not affect the conclusion concerning the relation between pressuriser pressure and level, but probably affected the pressure drop when the spray flow initiated. The size of this effect is not known, but is bounded by the calculation in which equilibrium was assumed.

6.7. Run-time characteristics

The semi-implicit numerics option was used in the calculations. Since the pumps were running, the primary flow was large enough for the calculation to be Courant limited thriughout the transient. The controlling volume was the node just downstream of the pumps, cell 150-01. The calculation ran with a cpu/transient ratio of about 2.1. Calculation to 600 s required 1236 s on the Harwell Cray-2.

7. CONCLUSIONS

i. Calculations have been performed of LOFT Experiment L9-3, a loss-of-feedwater anticipated transient without trip, in order to validate the code RELAP5/MOD2 for future use.

ii. The studies show that the course of transient can be fairly well simulated, but it is necessary that the initial inventory in the steam generator be correctly calculated. (It is not certain that this has been achieved here, although for plant analysis, the initial inventory would normally be known with some confidence, even though it is uncertain for LOFT).

iii. Several features of the transient calculated fairly accurately, in particular the time at which steam generator heat sink was essentially lost (given good estimate for initial inventory), the end point of the primary coolant temperature transient, and the effect of the PORV cycling in controlling the primary pressure (given correct discharge flow).

iv. The calculations suggest shortcomings in the RELAP5/MOD2 treatment of interphase drag. This led to too sudden a loss of steam generator heat sink which could not be overcome by renodalisation of the lower part of the steam generator.

v. There is reason to believe that the phases may be close to equilibrium during spray operation. The calculated pressure rose too rapidly in relation to the liquid level, Thus affecting the sequence of pressuriser filling and PORV, SRV actuation, and hence the mass and energy flows. The main cause of this discrepancy appears to be the under-representation of heat removal from the vapour during spray operation.

vi. Simulation of the event sequence and timings for this transient is fairly challenging, due to the number of events and setpoints reached in a short space of time. The uncertainty in the pressure response during spray operation, and discrepancy in the steam generator heat transfer during boildown, made it difficult to obtain exact agreement for the timings for which setpoints were reached. Calculation of the event sequence depends also on how setpoints are defined (e.g. on time, pressure in certain location, other setpoint, etc.). This could cause difficulties in some plant applications where some setpoints are defined on a condition while others might be on time.

vii. Use of the RELAP5/MOD2 points kinetics model proved a viable means of calculating the power transient. This ensured that the reactivity and thermal hydraulic transients remained in step.

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Table 1 Initial Conditions for Experiment L9-3

PARAMETER		MEASURED	CALCULATED	
			PRELIMINARY	REVISED
PRIMARY COOLANT SYSTEM				
Mass flow	kg/s	467.6	467.7	467.7
Hot leg pressure	MPa	14.98	14.95	14.94
Temperature across core	K	19.4	19.2	19.2
Cold leg temperature	K	557.0	559.0	558.6
Hot leg temperature	K	576.4	578.2	577.8
Boron concentration	ppm	694	--	--
REACTOR VESSEL				
Power level	MW	48.7	48.7	48.7
PRESSURISER				
Steam volume	m3	0.40 a	0.473	0.437
Liquid volume	m3	0.53 a	0.515	0.551
Liquid temperature	K	615.2	613.4	613.5
Pressure	MPa	14.98	14.91	14.91
Liquid level	m	1.00	0.975	1.039
STEAM GENERATOR				
Liquid level	m	3.15	3.15	3.15
Liquid temperature	K	544.4	544.6	544.5
Pressure	MPa	5.61	5.62	5.62
Mass flow	kg/s	25.7	25.45	25.46

a As given in Experiment Data Report; revised estimates are 0.45 and 0.55 m3 for vapour and liquid volumes.

Table 2 Sequence of Events for Experiment L9-3

EVENT	TIME (seconds)		
	ACTUAL	CALCULATED	
		PRELIM	REVISED
Main feedwater pump tripped off	0.0	0.0	0.0
Pressuriser spray valve cycling initiated	29.5	23.0	41.5
Steam generator MSCV closed	67.3	67.3 a	67.6 b
Experiment primary PORV opened	73.8	60.2 c	67.0 d
Pressuriser liquid level reached top of indicating range (1.83 m above bottom)	90.0	----	95.6
Steam generator liquid level reached bottom of indicating range (0.25 m above bottom)	94.5	60.6	68.1
Experiment primary SRV opened	96.8	64.5 c	75.0 d
Experiment primary SRV closed	107	76.4 c	82.8 d
Experiment primary PORV closed	123	----	159.2 d
Experiment primary PORV cycling initiated	125.4	----	163.1 d
Experiment PORV cycling terminated	208	----	e
End of ATWS phase / start of recovery	601.1	----	----
End of calculation	----	----	600.0

a setpoint defined by time

b setpoint defined by SG pressure

c setpoint defined by nominal pressure

d setpoint defined by actual pressure

e was still cycling at 600 s

Figures

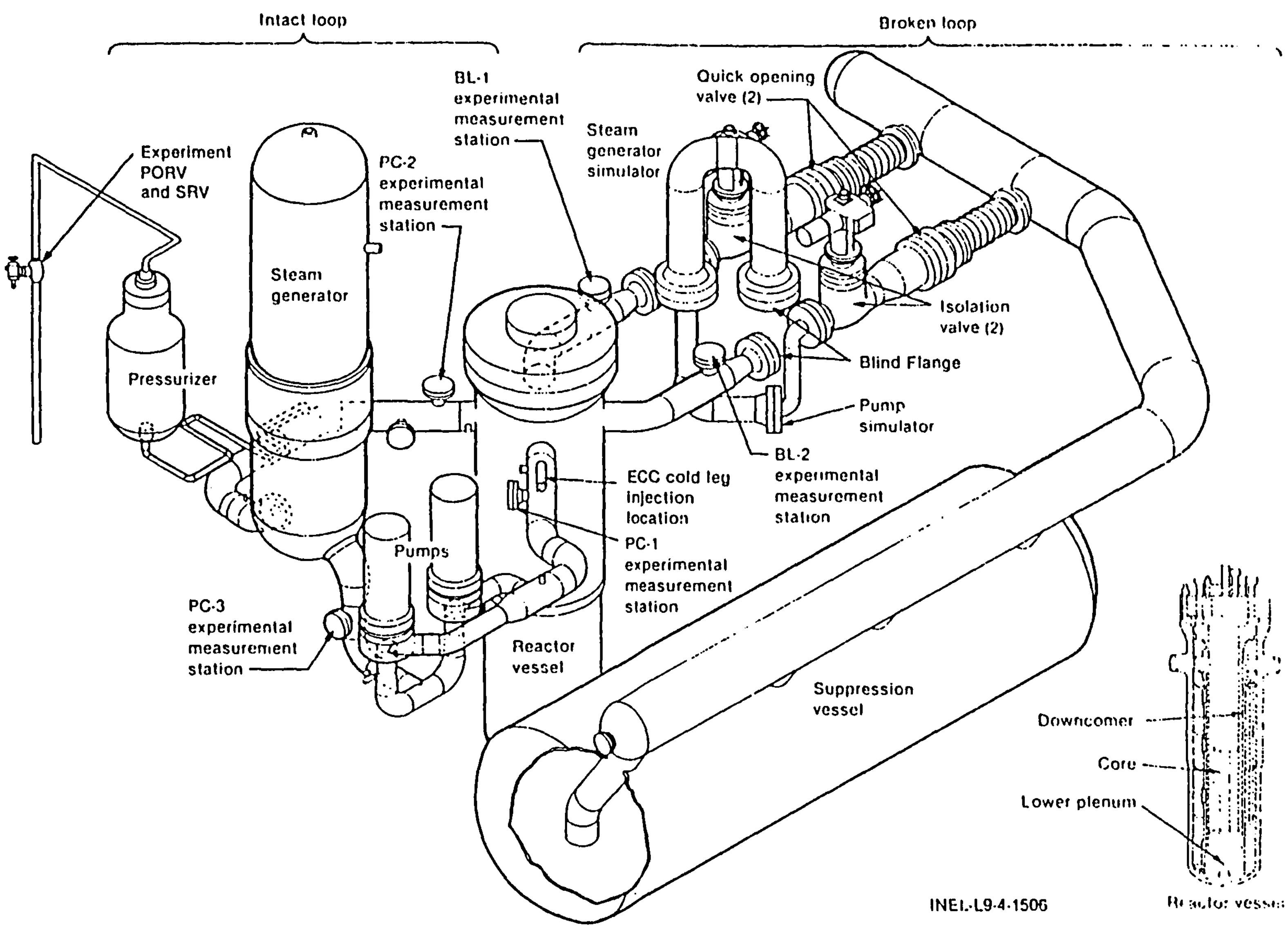

Figure 1. Axonometric projection of LOFT system.

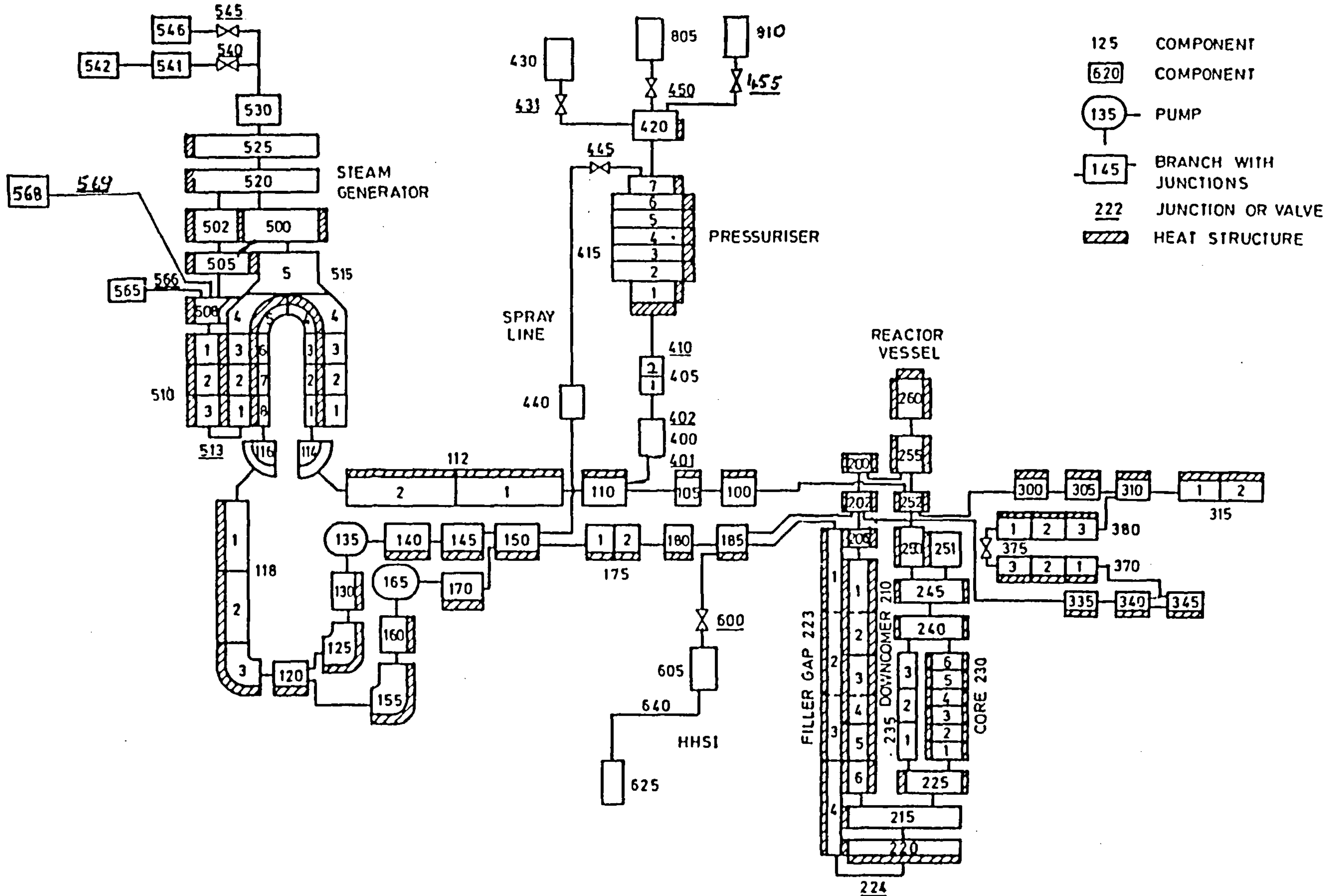

FIGURE 2 - RELAP 5/MOD 2 NODING DIAGRAM FOR CALCULATION OF LOFT TEST L9-3

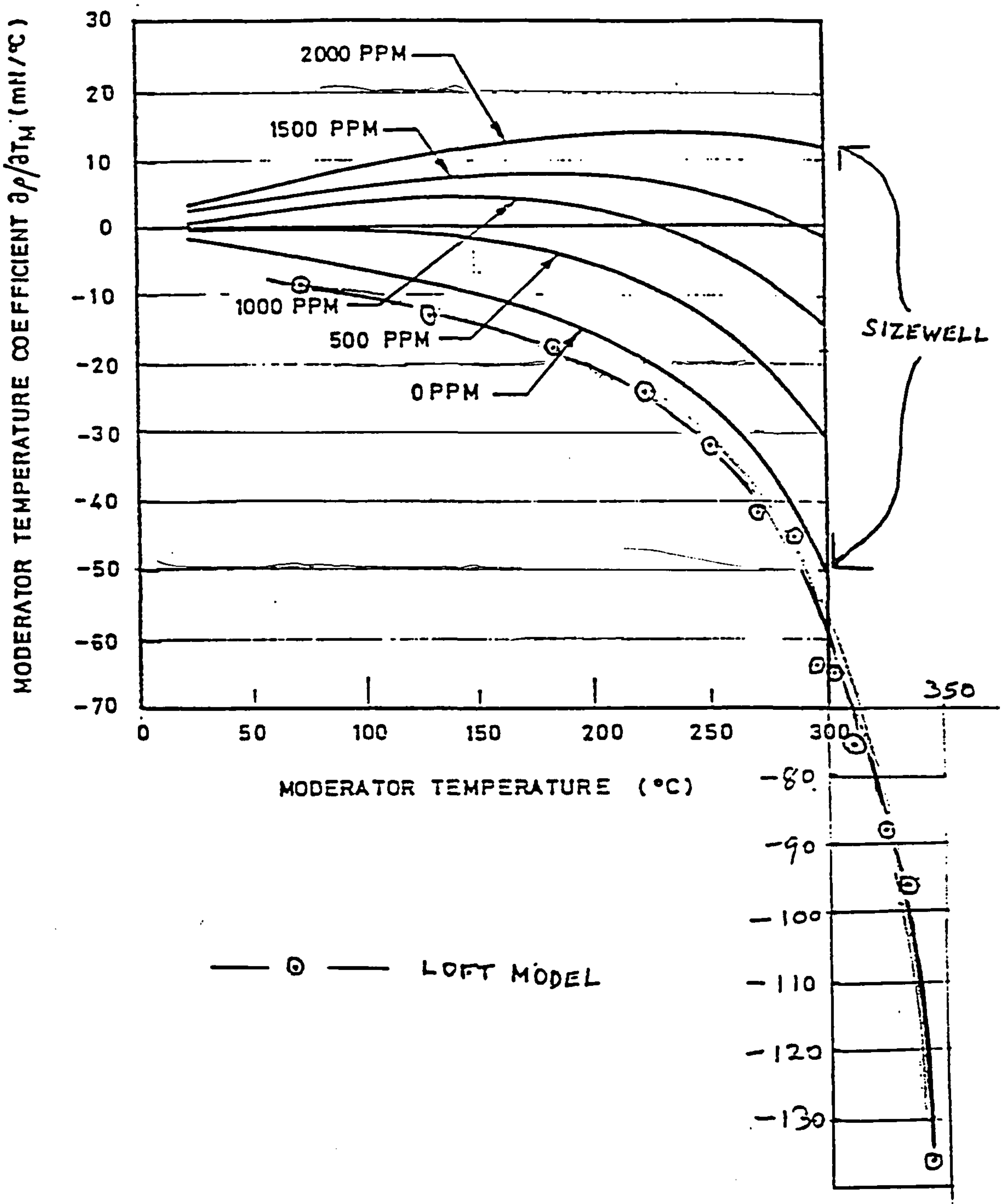

Figure 3. Comparison of LOFT Core reactivity with Sizewell 'B' at End-of-life

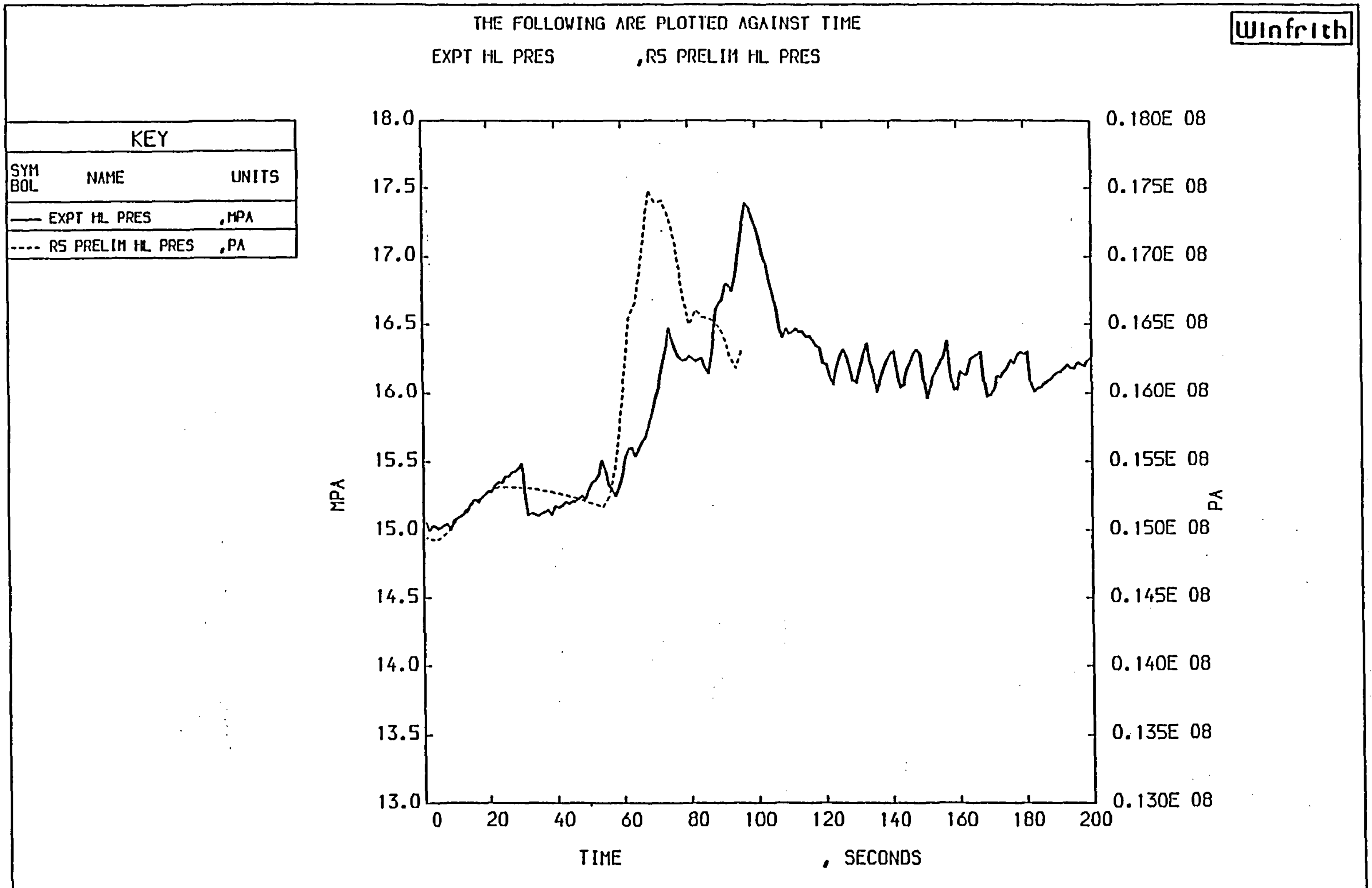

Figure 4. L9-3 HOT LEG PRESSURE

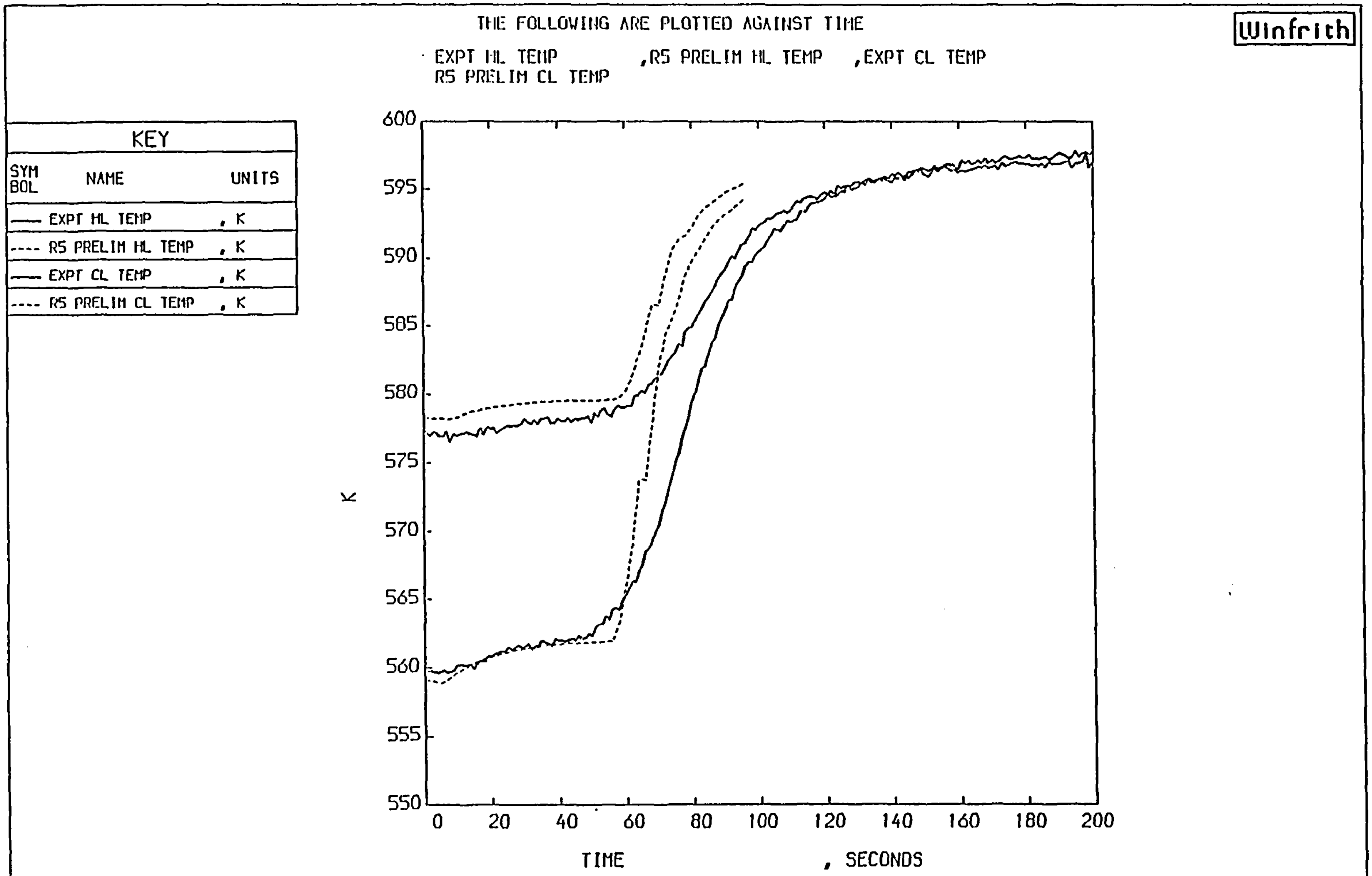

Figure 5. L9-3 HOT AND COLD LEG TEMPERATURE

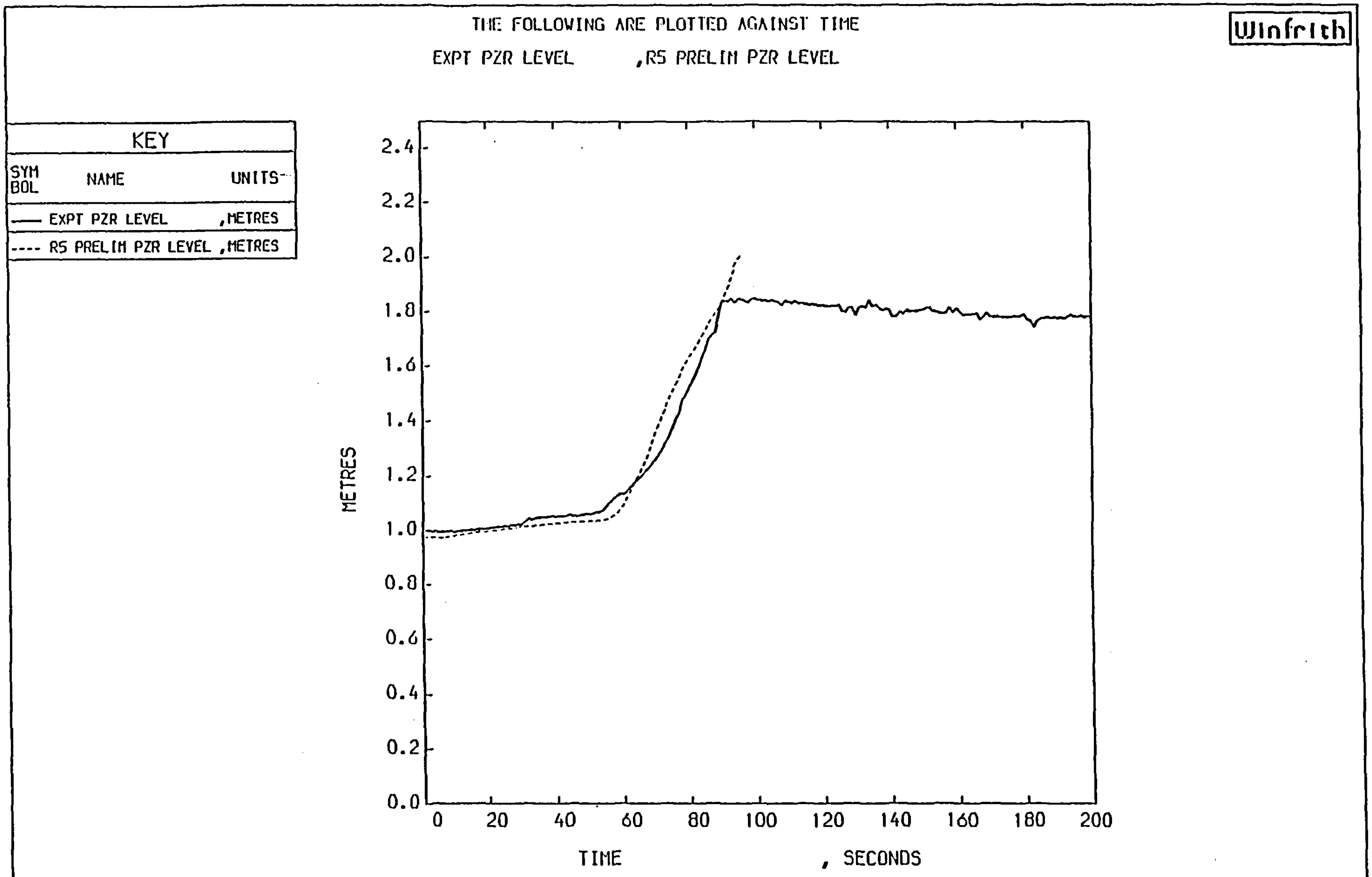

Figure 6. L9-3 PRESSURISER LEVEL

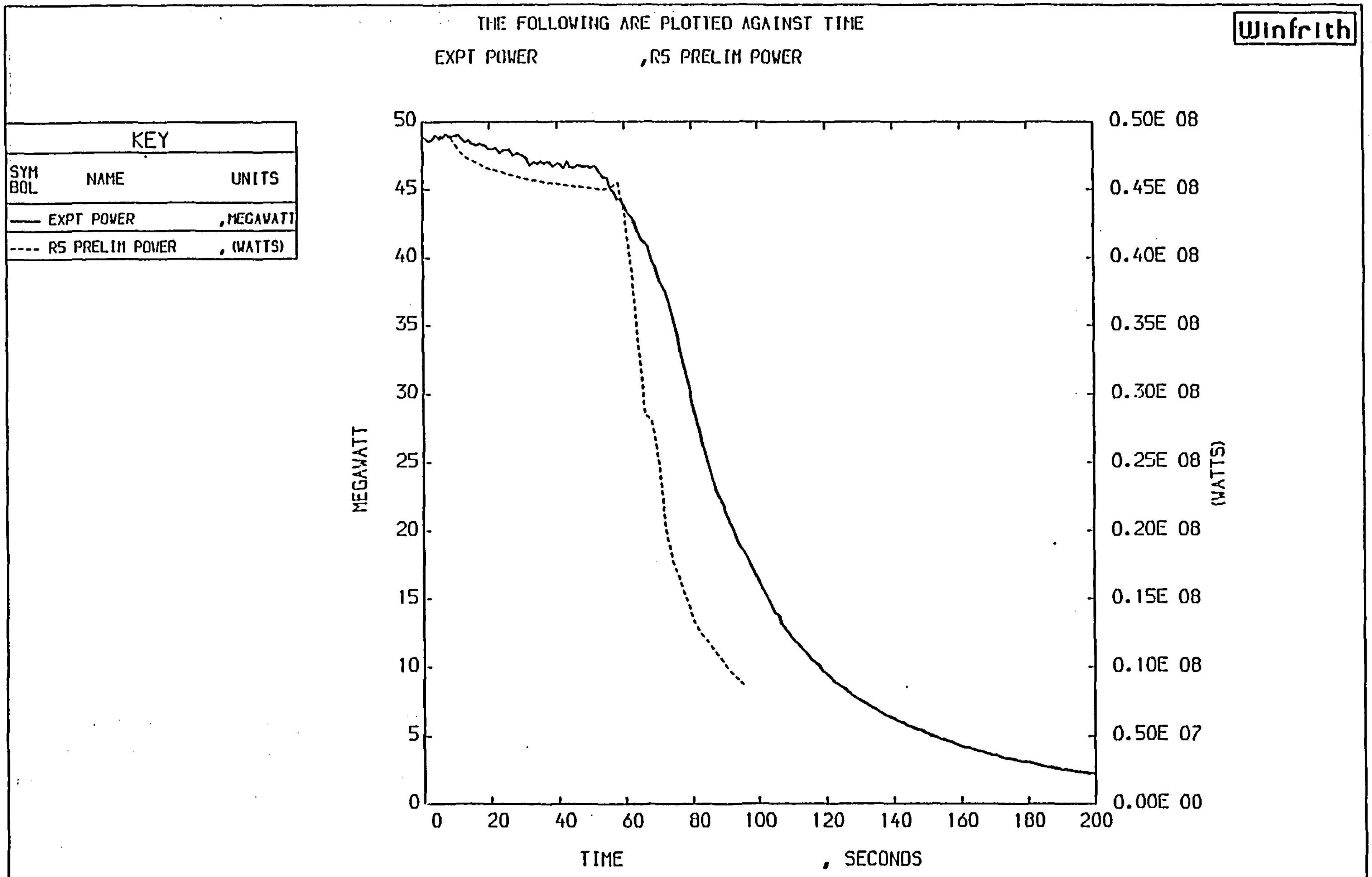

Figure 7. L9-3 REACTOR POWER

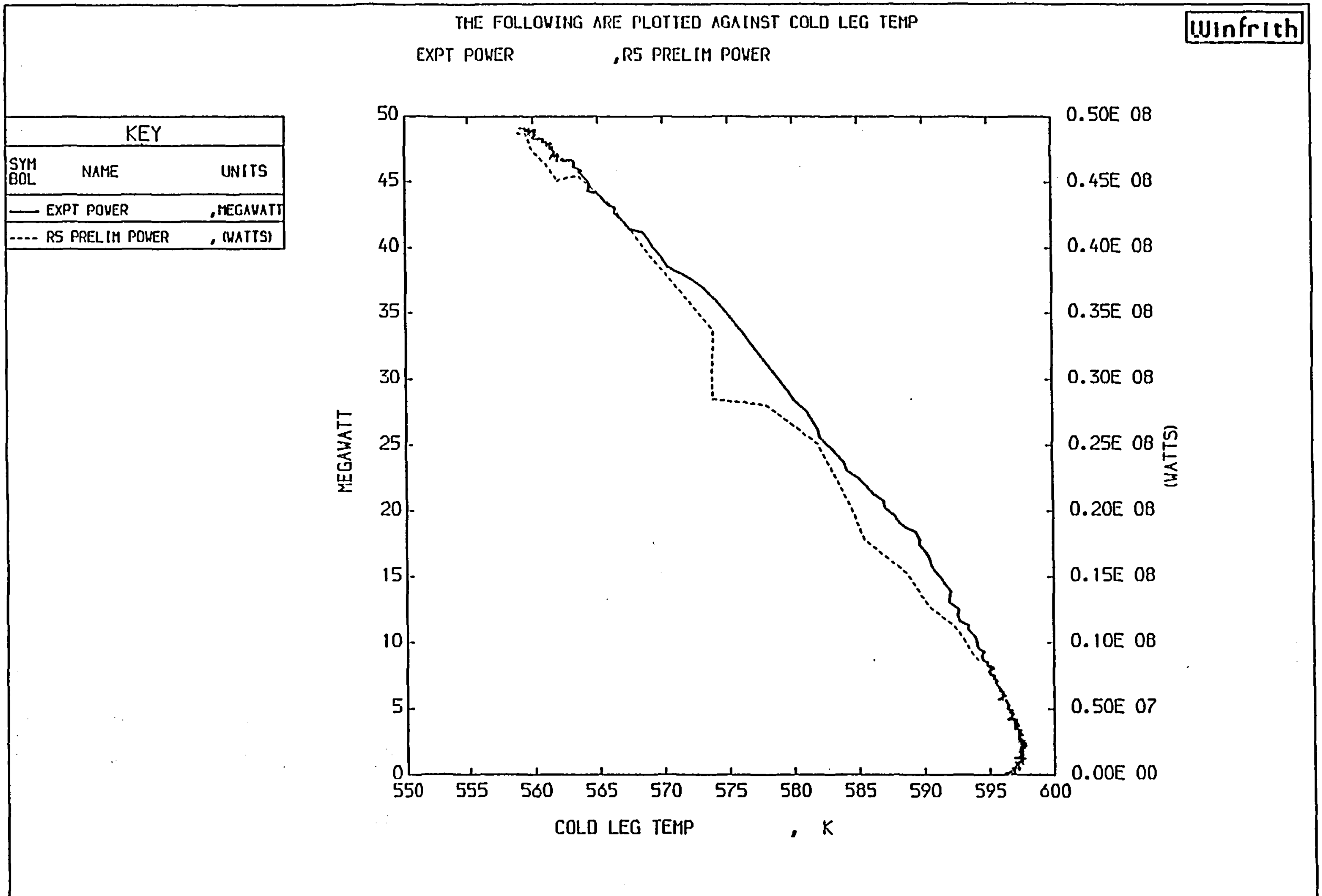

Figure 8. L9-3 REACTOR POWER VS COOLANT TEMPERATURE

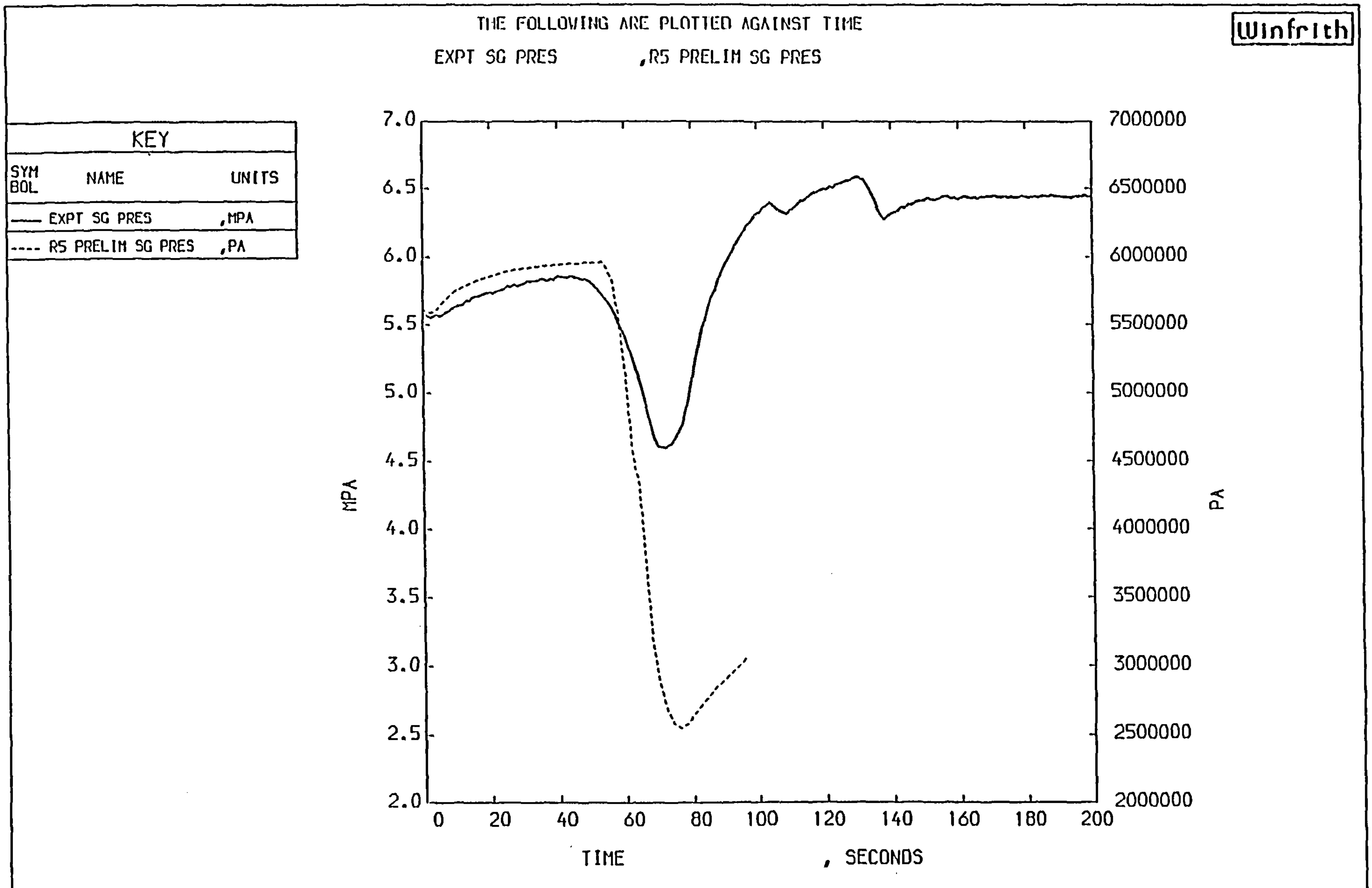

Figure 9. L9-3 STEAM GENERATOR PRESSURE

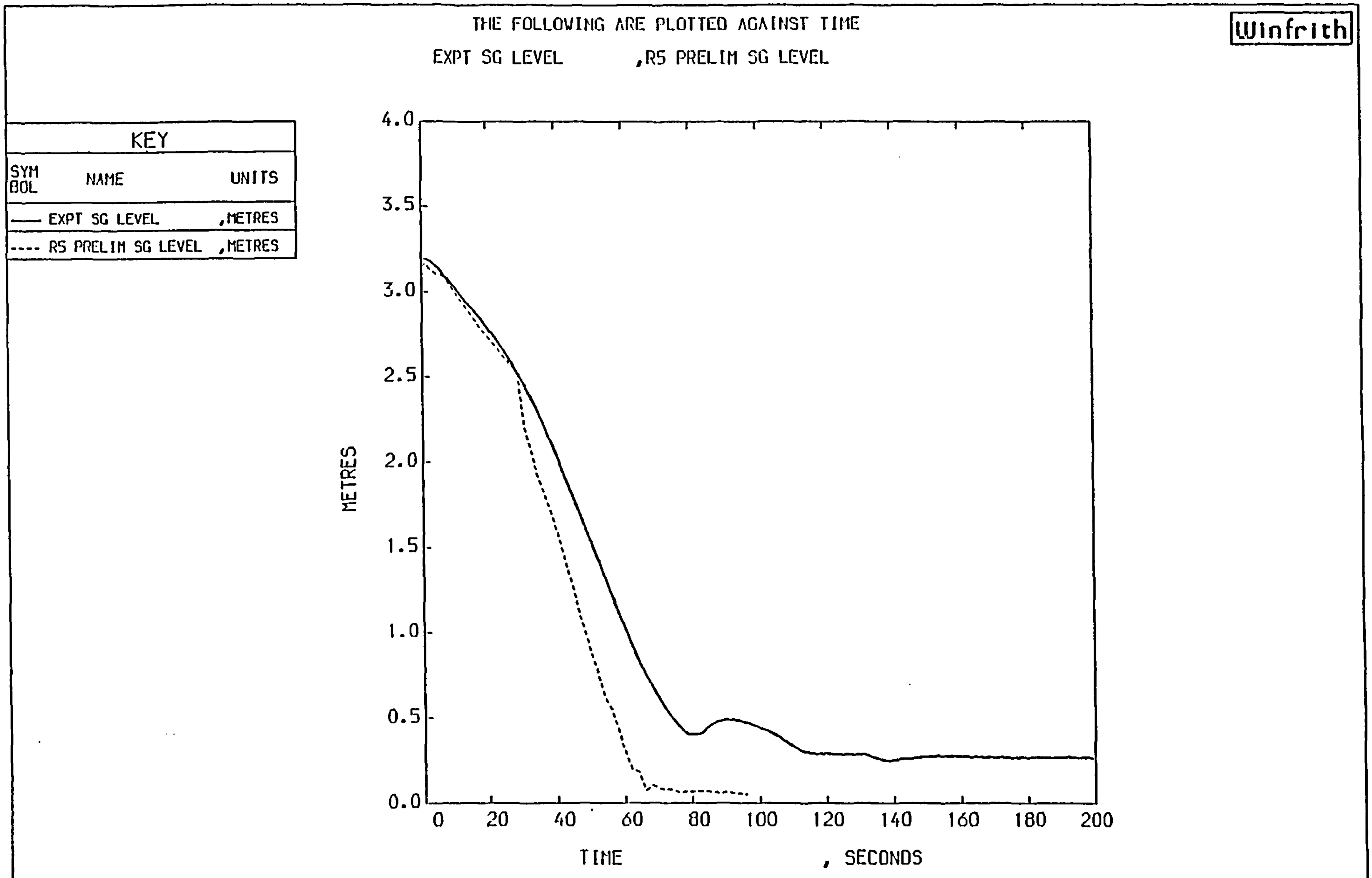

Figure 10. L9-3 STEAM GENERATOR LEVEL

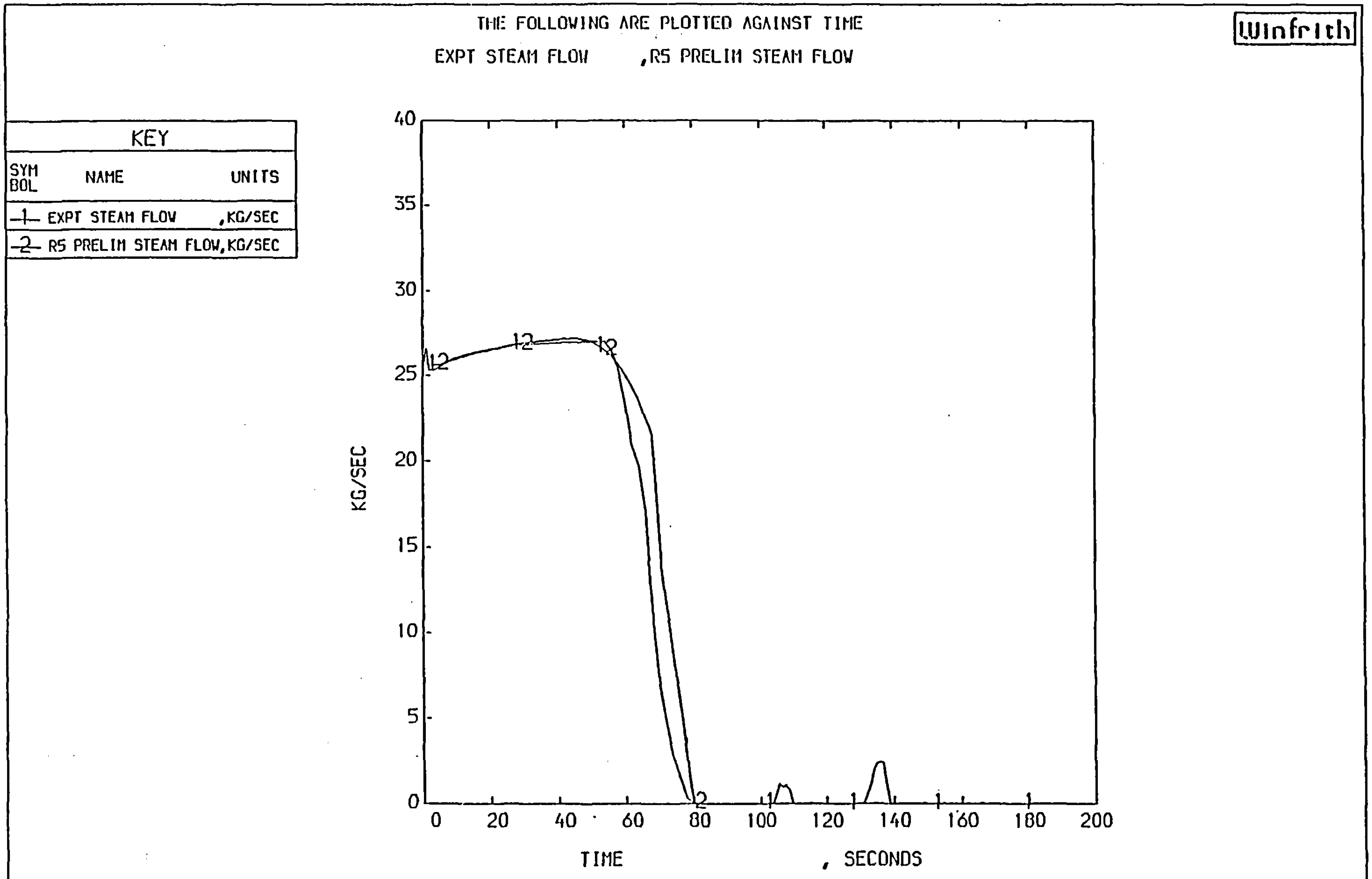

Figure 11. L9-3 STEAM FLOW

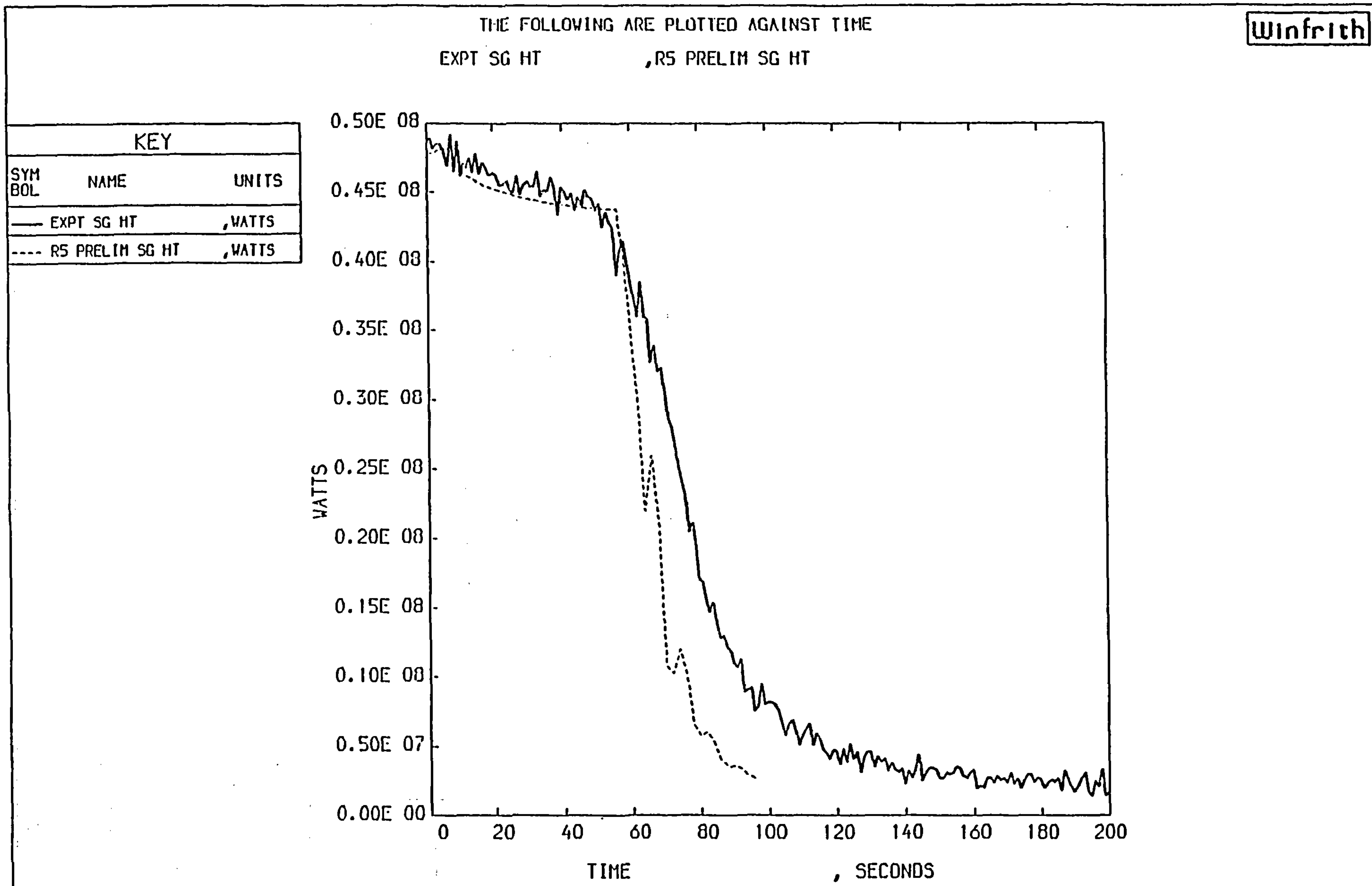

Figure 12. L9-3 STEAM GENERATOR HEAT TRANSFER

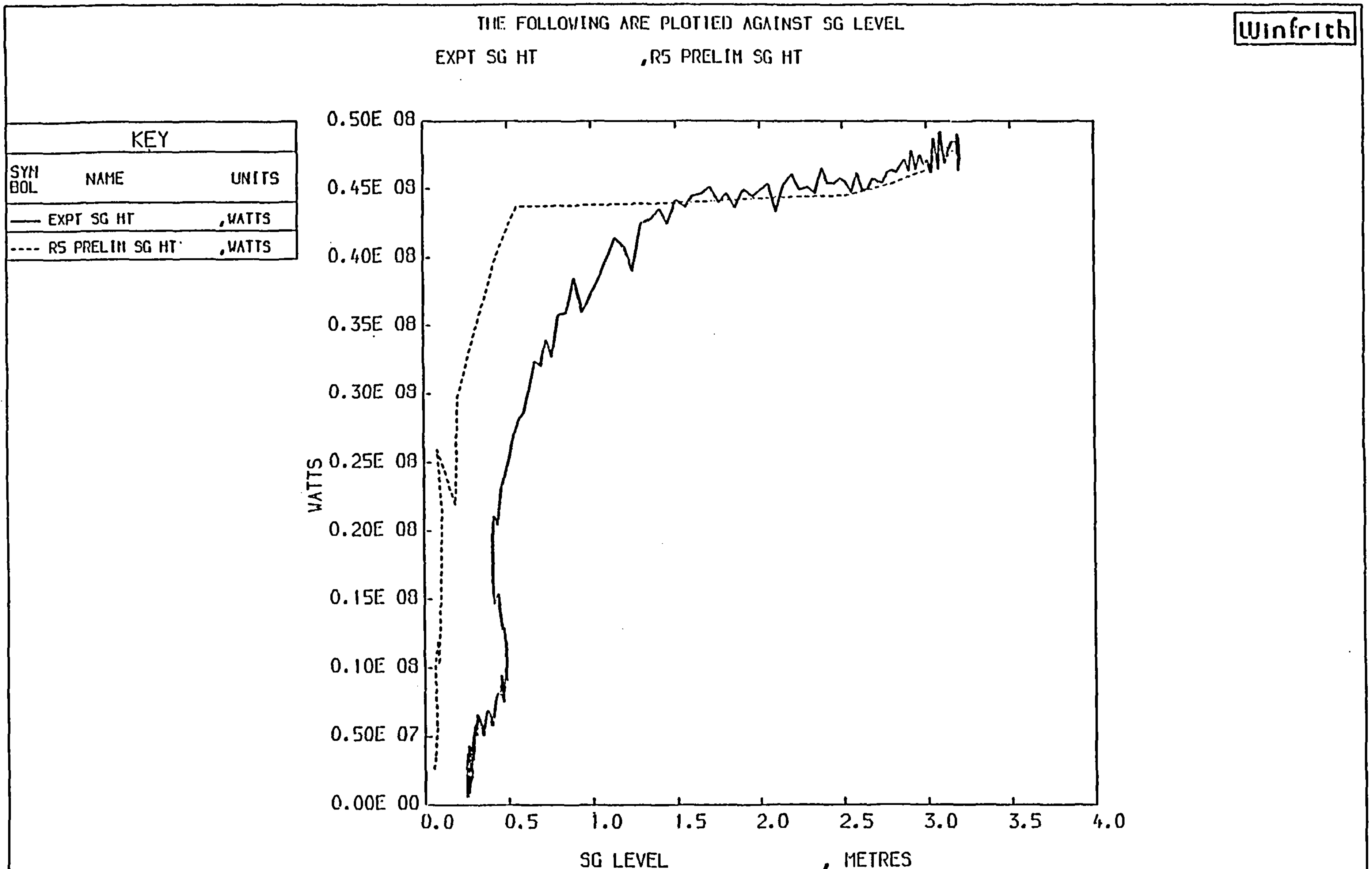

Figure 13. L9-3 SG HEAT TRANSFER VS LEVEL

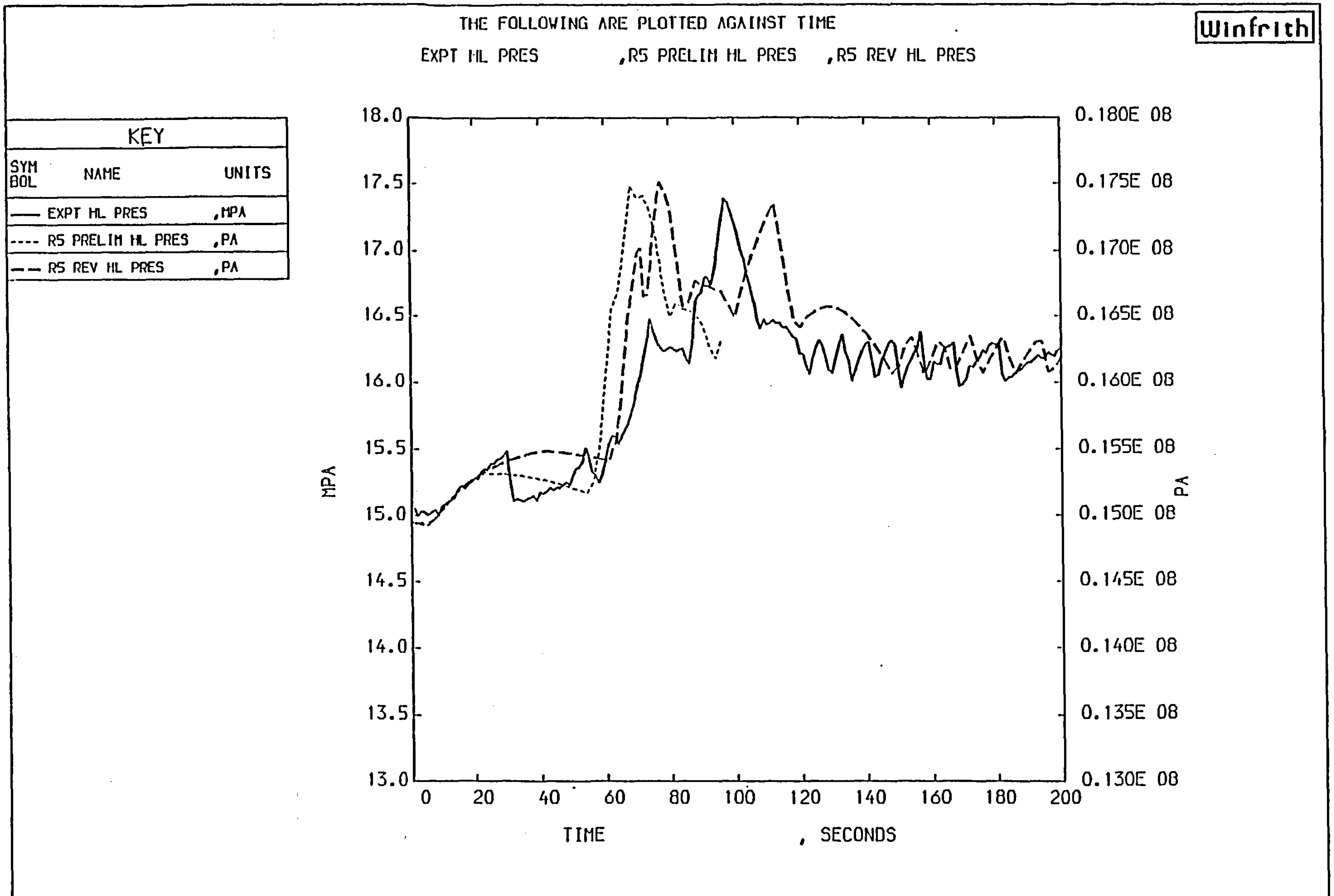

Figure 14. L9-3 HOT LEG PRESSURE - EFFECT OF MODEL CHANGES

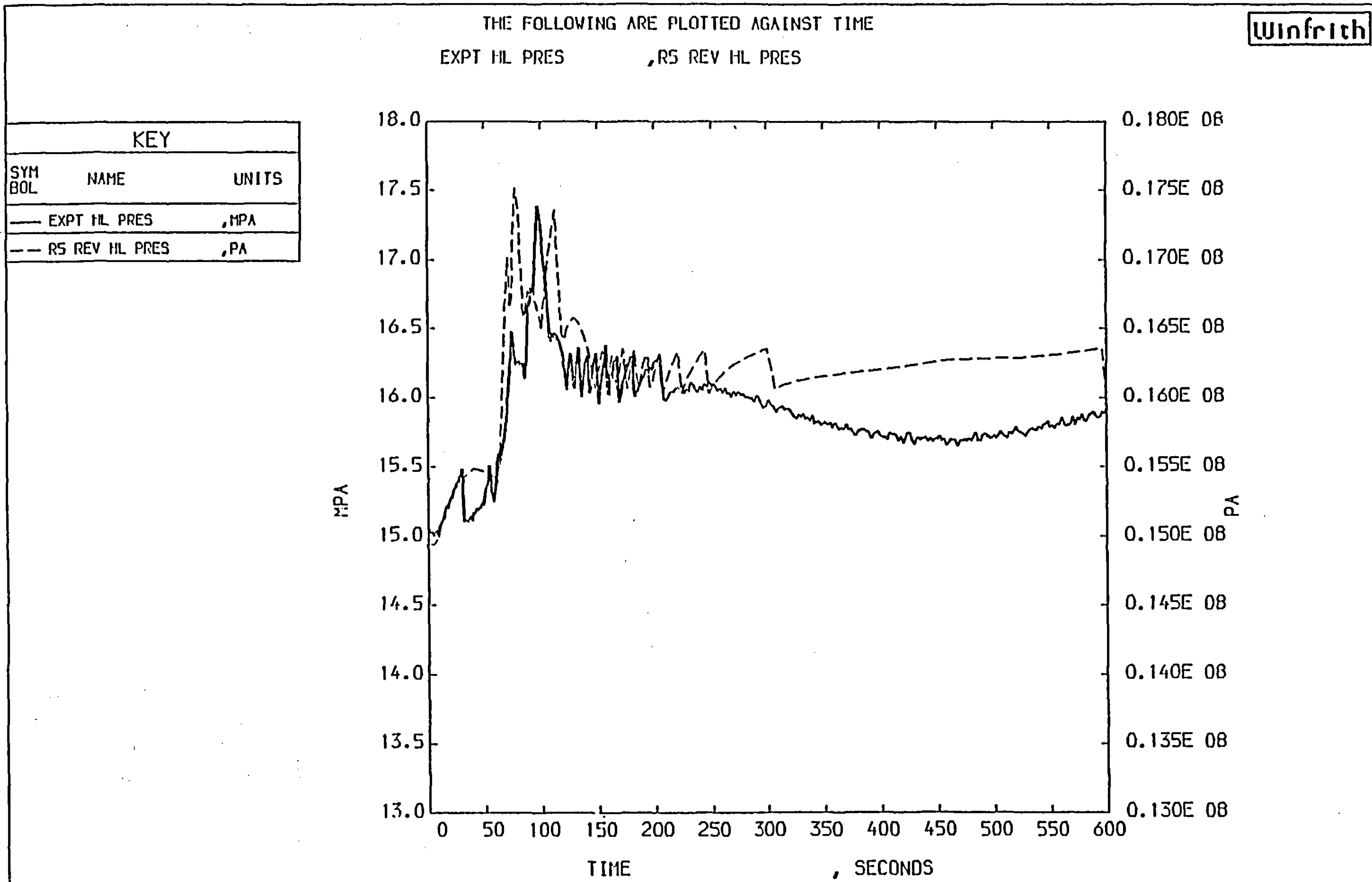

Figure 15.L9-3 HOT LEG PRESSURE - REVISED MODEL

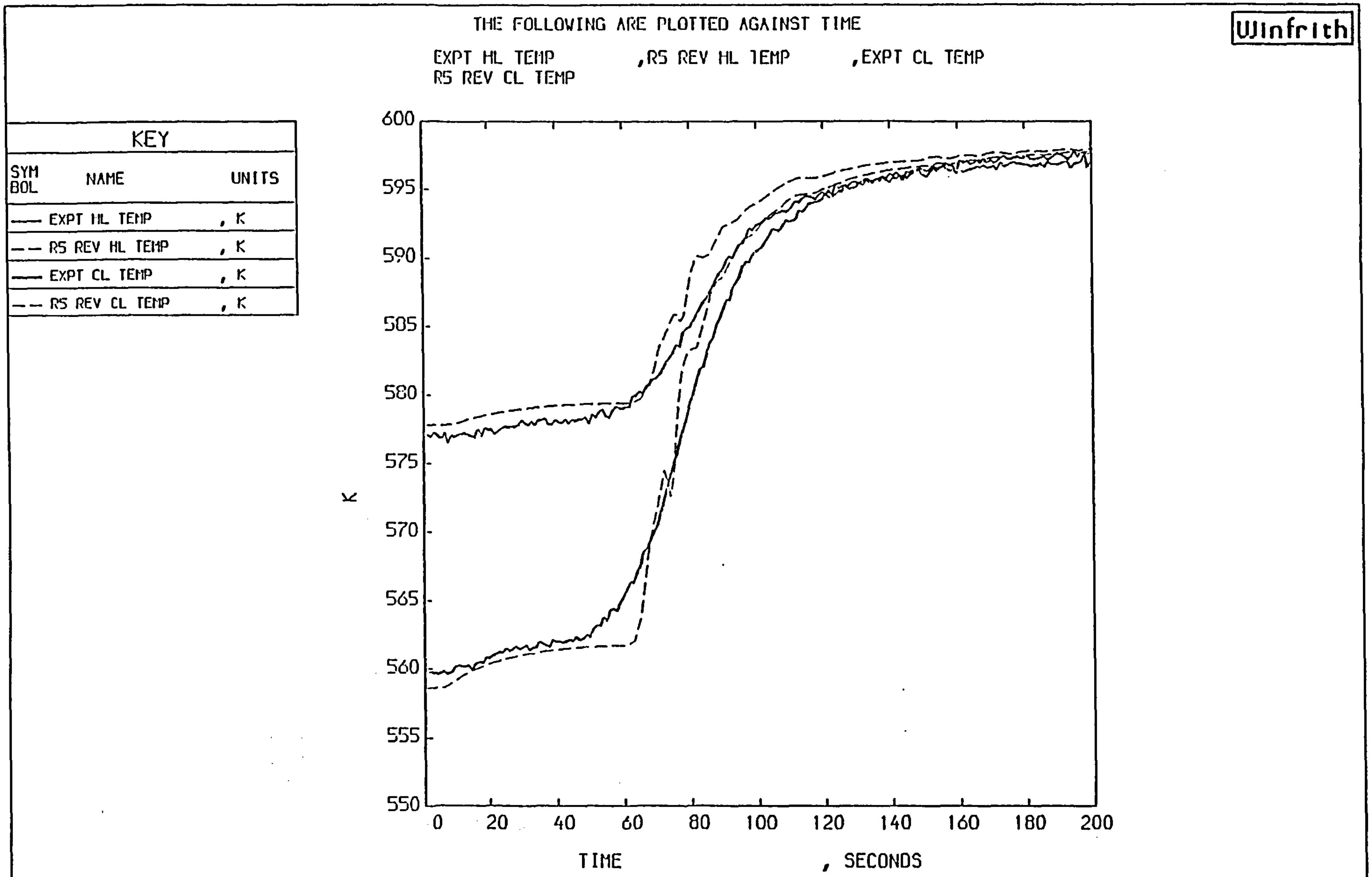

Figure 16. L9-3 HOT AND COLD LEG TEMPERATURE - REVISED MODEL

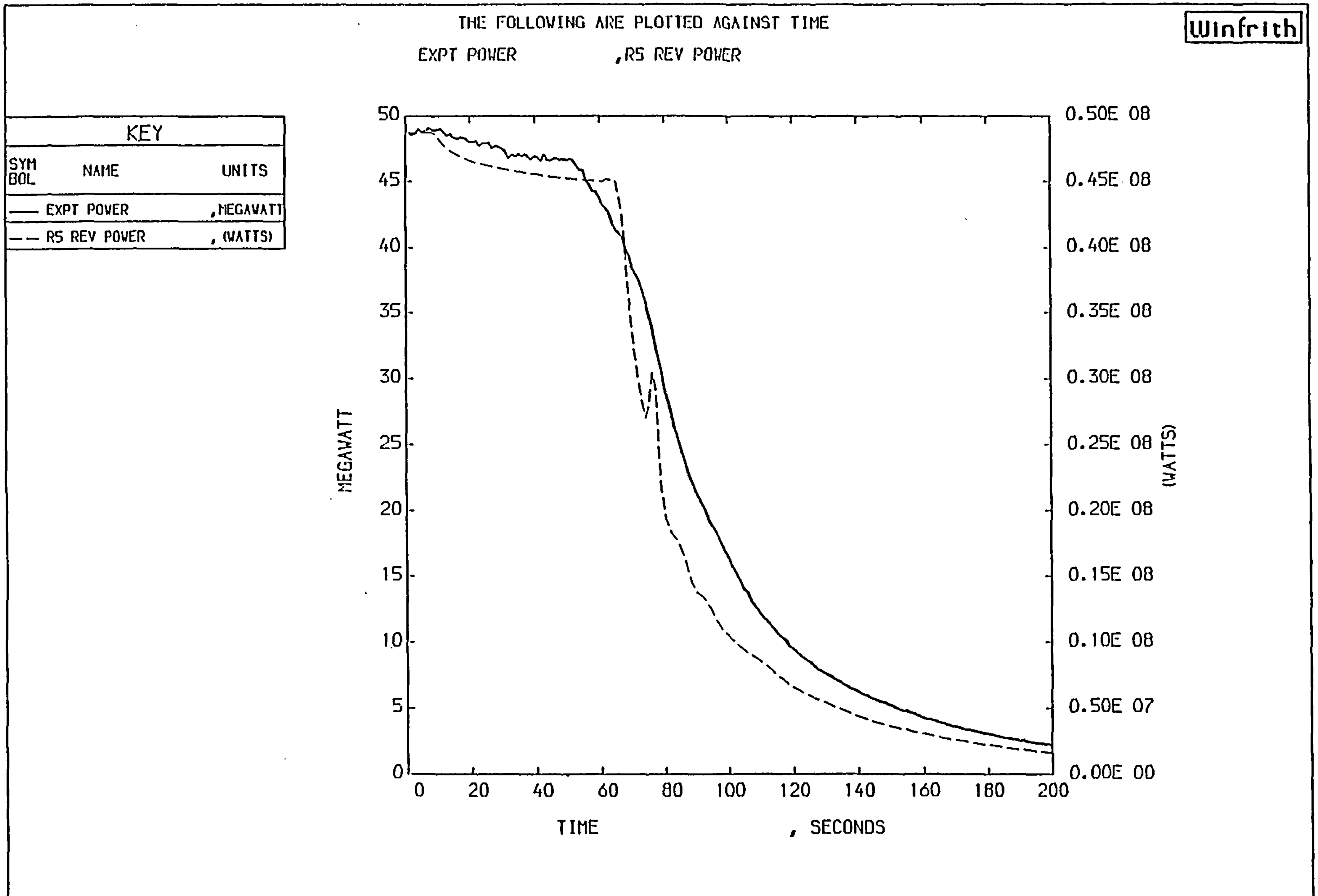

Figure 17. L9-3 REACTOR POWER - REVISED MODEL

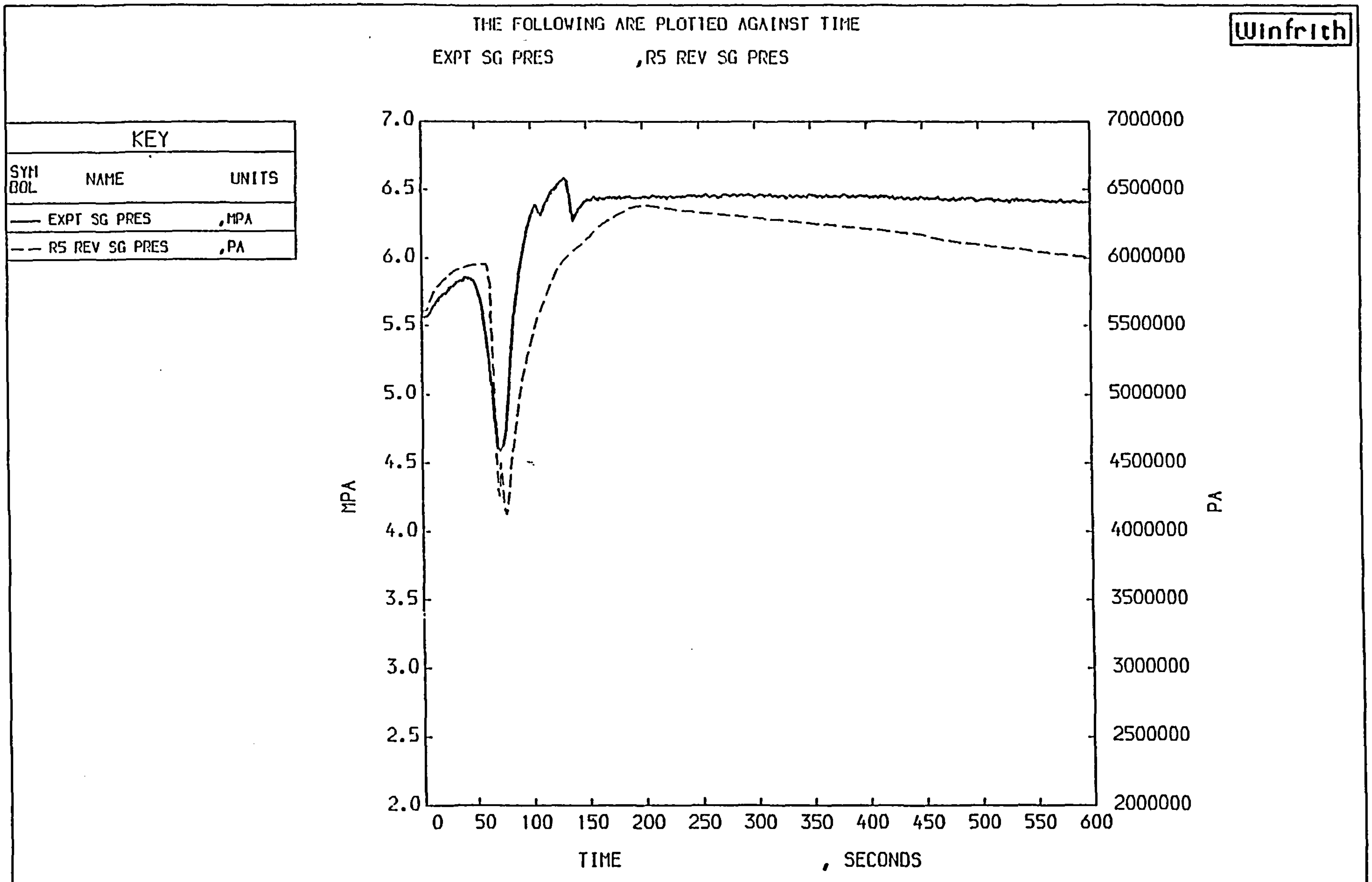

Figure 18. L9-3 STEAM GENERATOR PRESSURE - REVISED MODEL

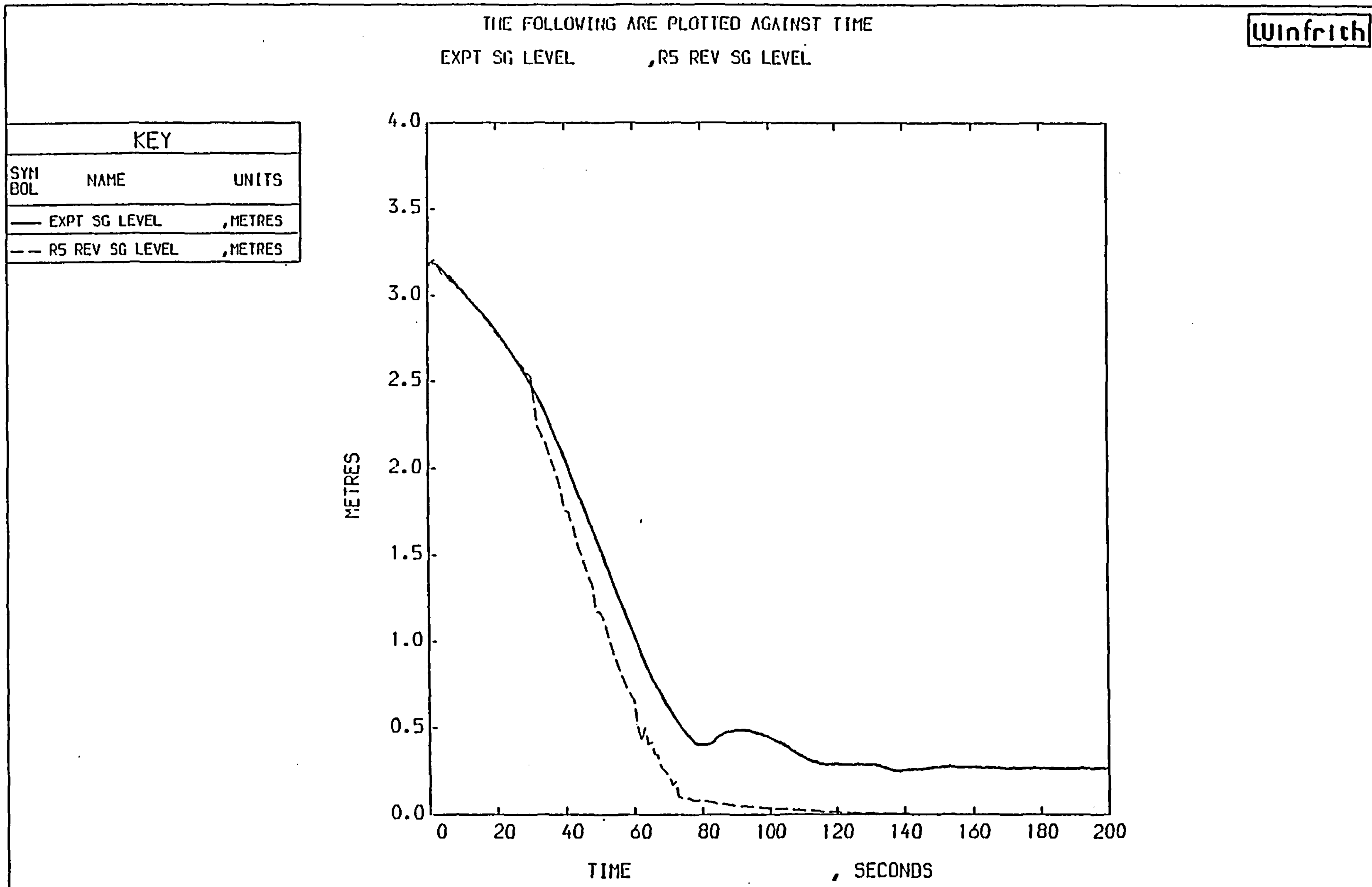

Figure 19. L9-3 STEAM GENERATOR LEVEL - REVISED MODEL

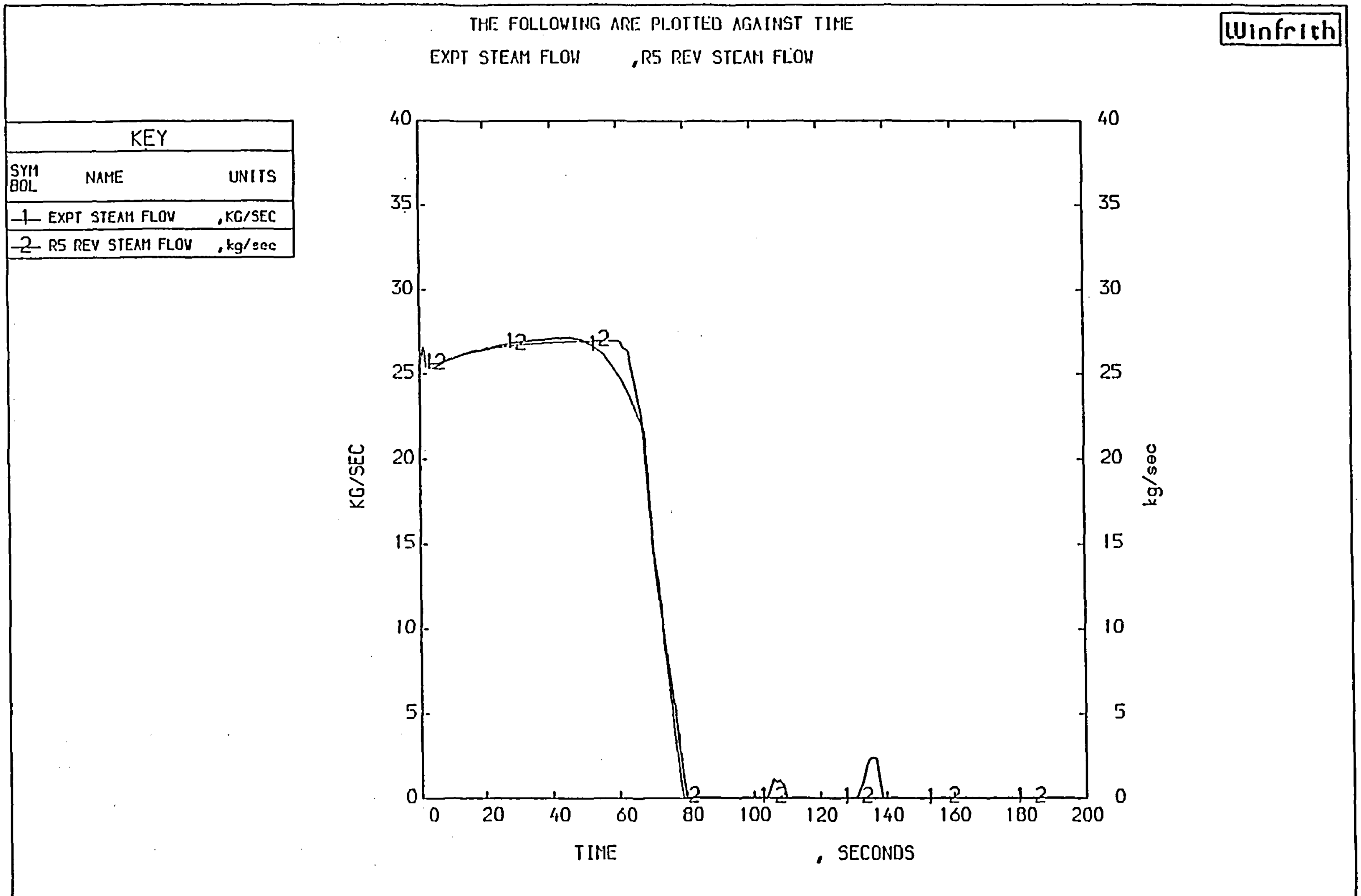

Figure 20. L9-3 STEAM FLOW - REVISED MODEL

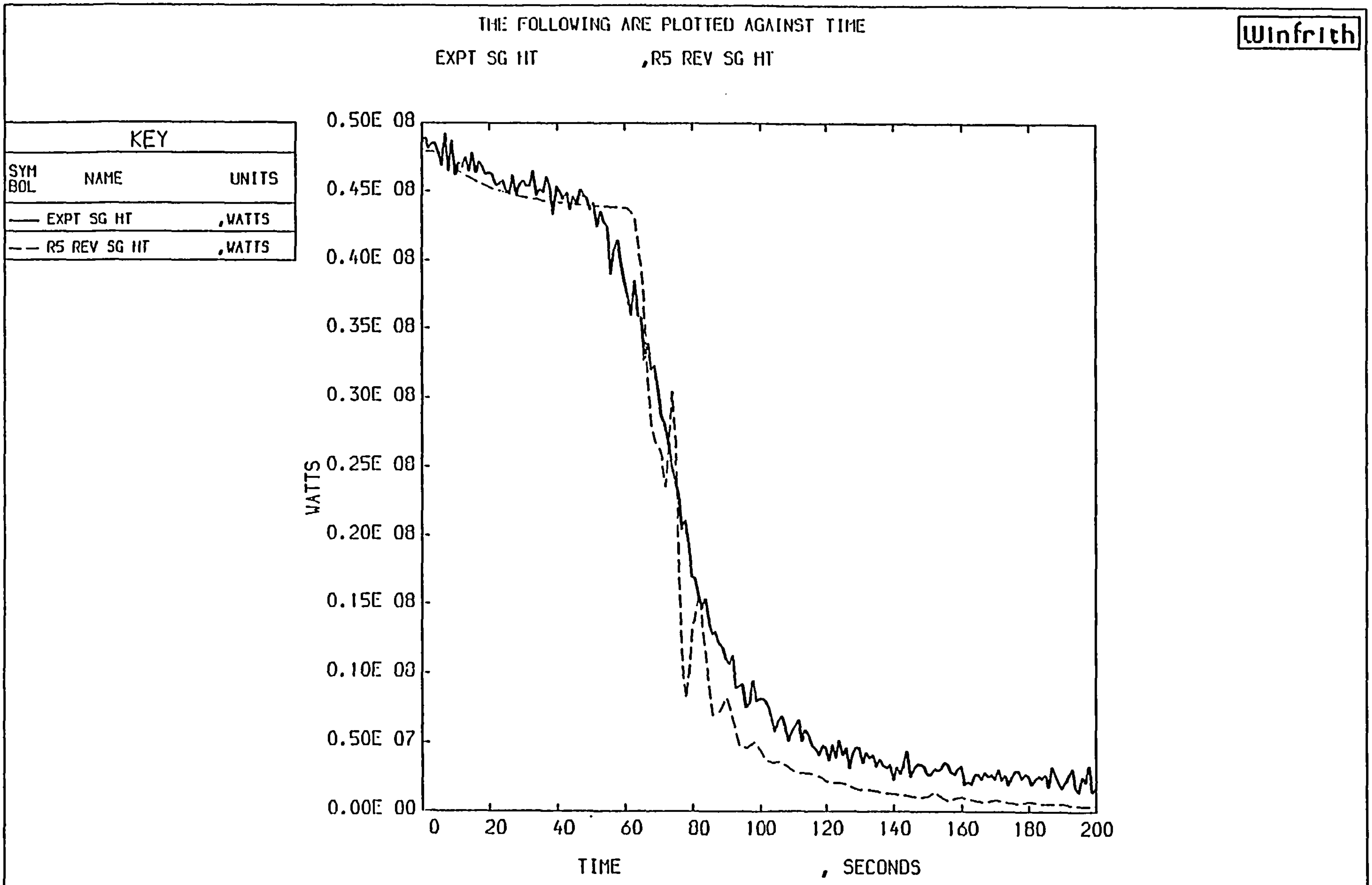

Figure 21. L9-3 STEAM GENERATOR HEAT TRANSFER - REVISED MODEL

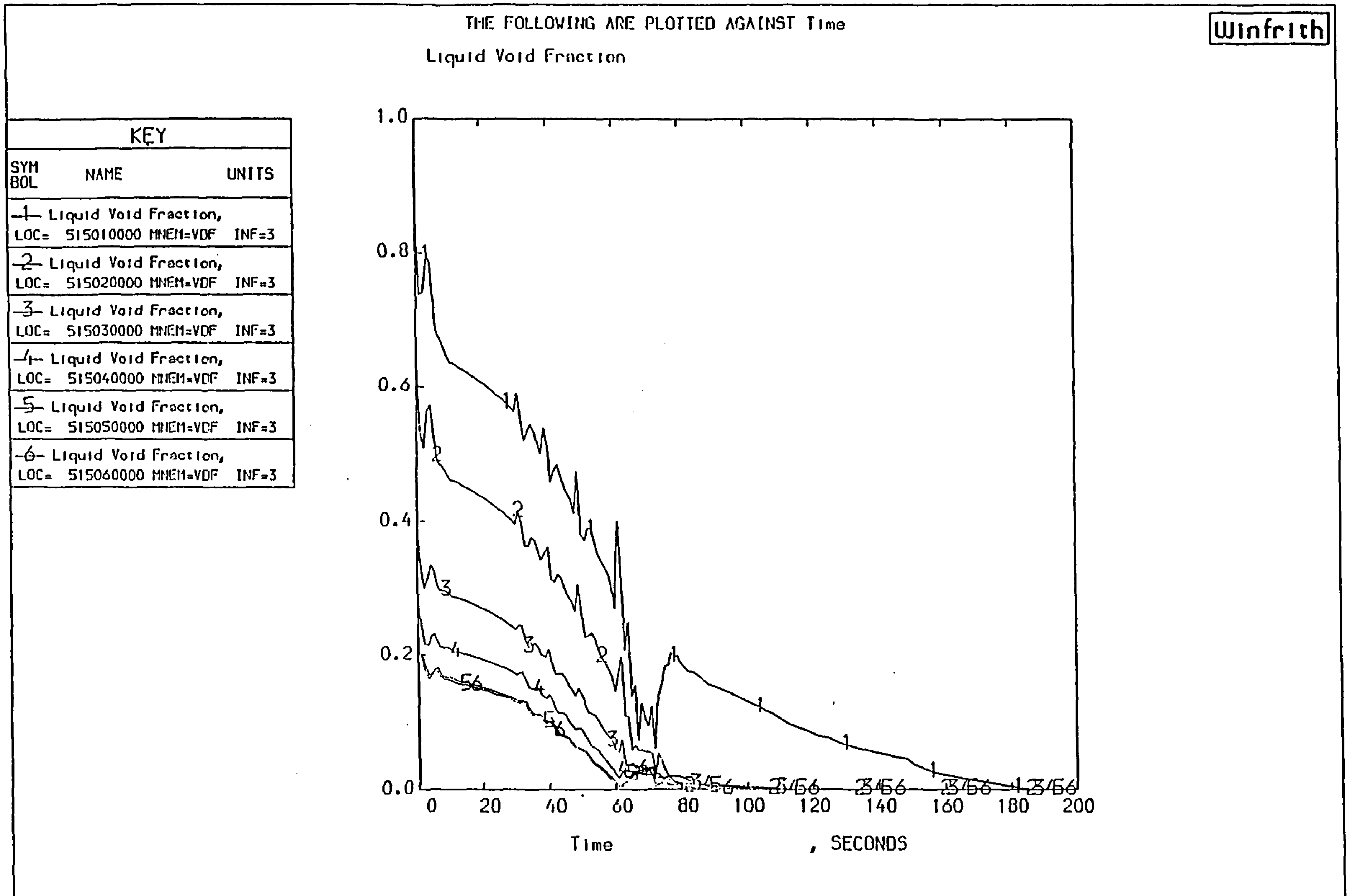

Figure 22. L9-3 CALCULATED LIQUID FRACTION IN RISER NODES - REVISED MODEL

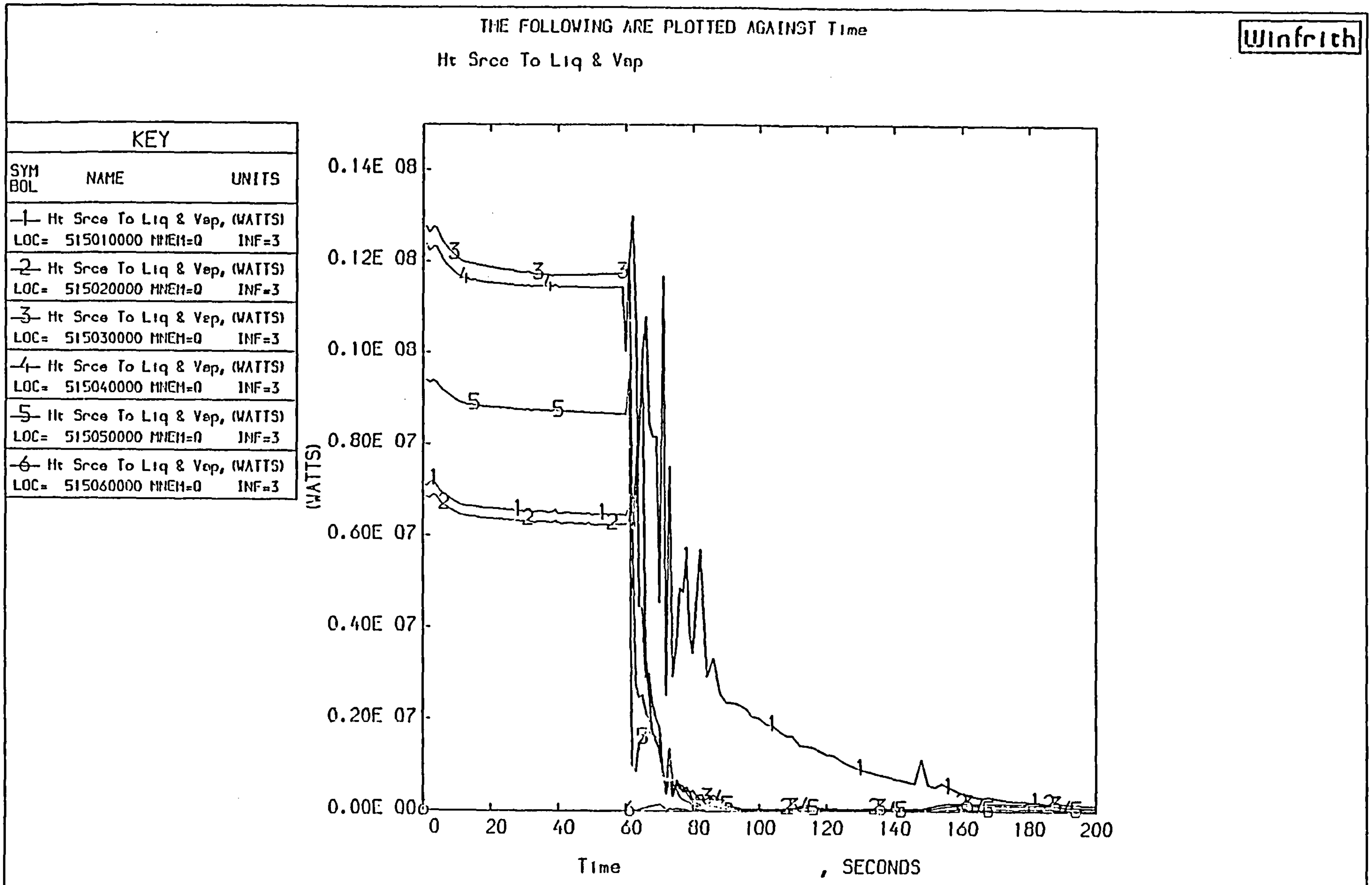

Figure 23. L9-3 CALCULATED HEAT TRANSFER IN RISER NODES - REVISED MODEL

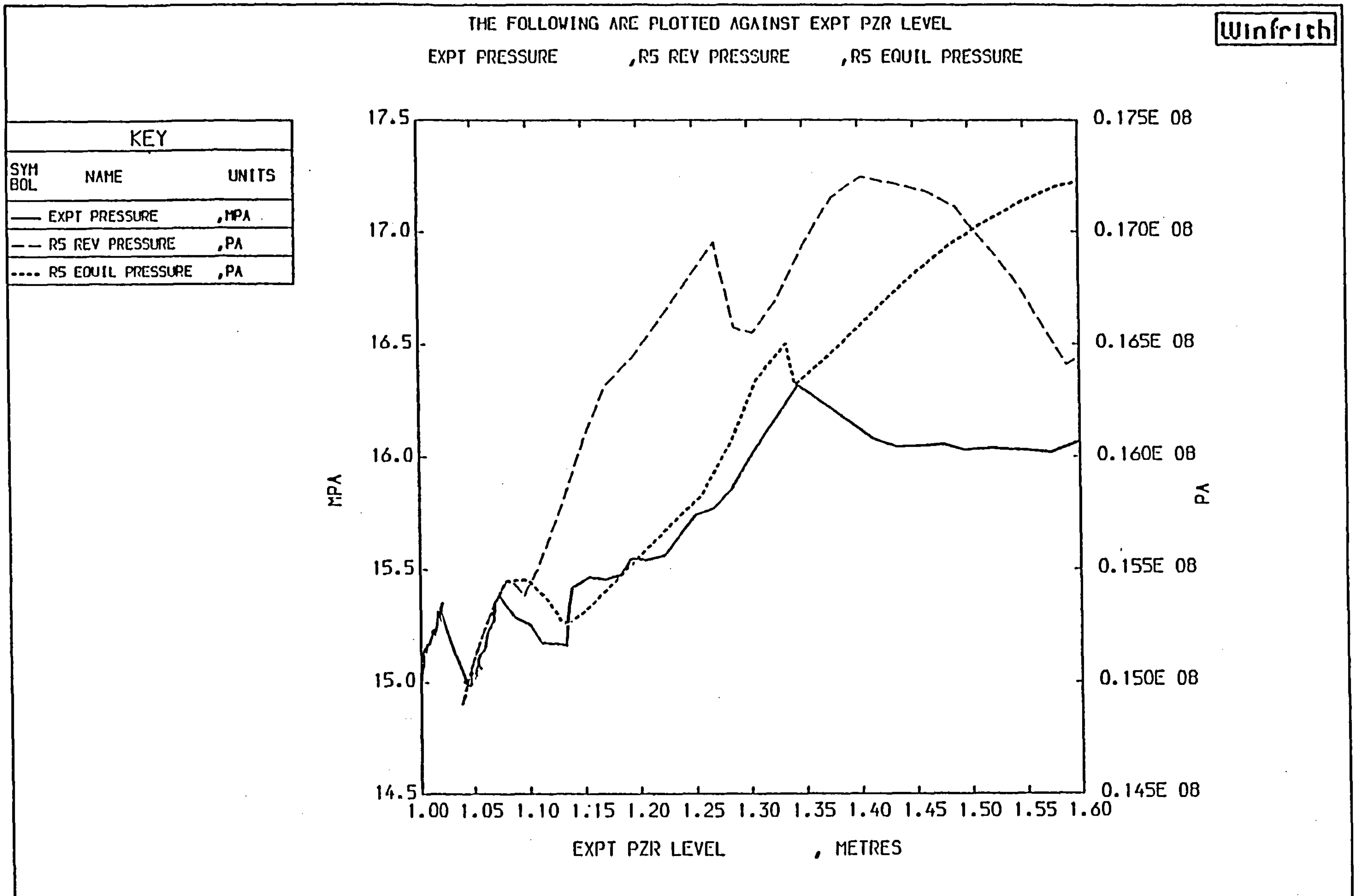

Figure 24. PRESSURISER PRESSURE VS LEVEL - EFFECT OF EQUILIBRIUM

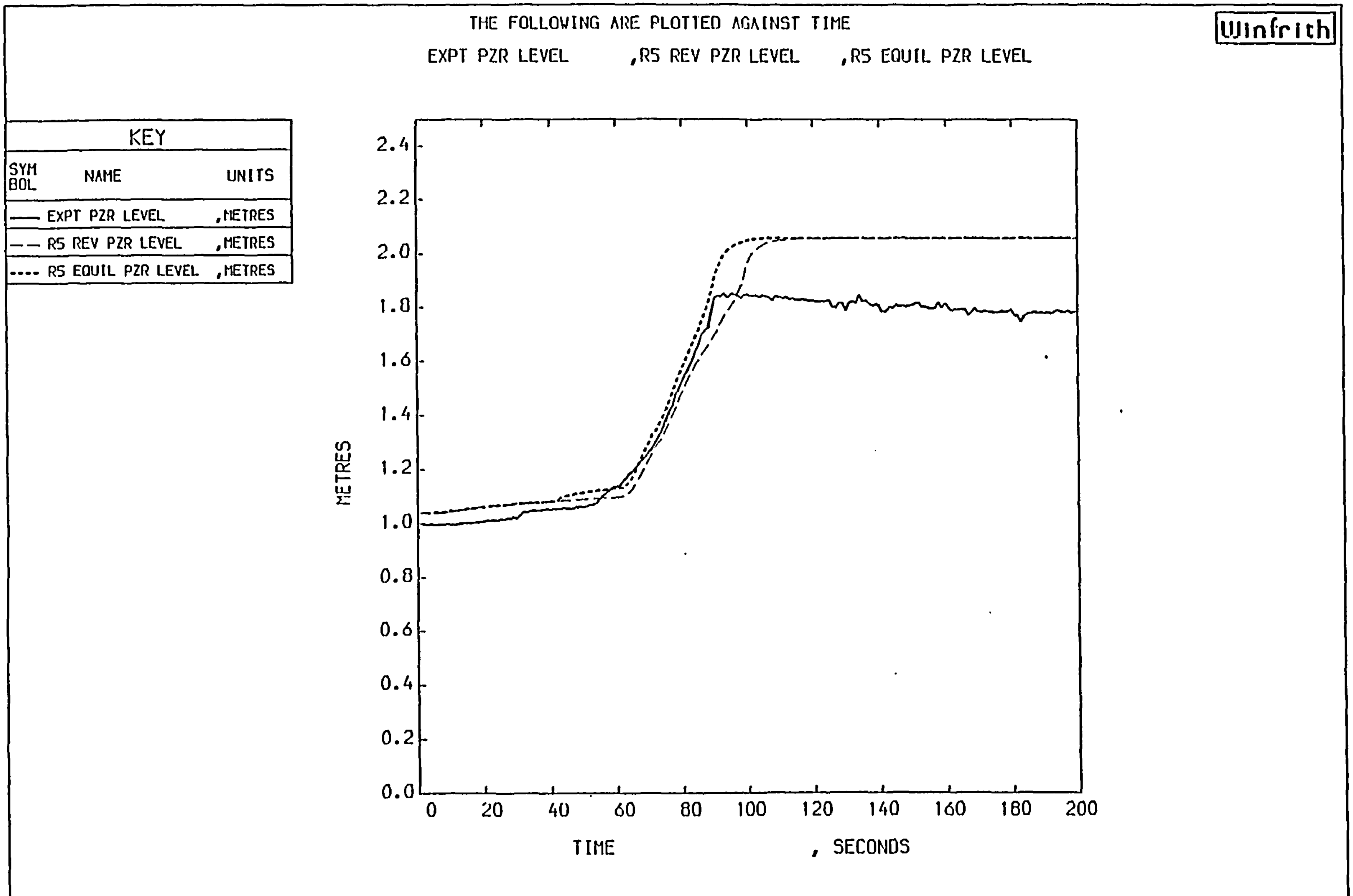

Figure 25. L9-3 PRESSURISER LEVEL -EFFECT OF EQUILIBRUM

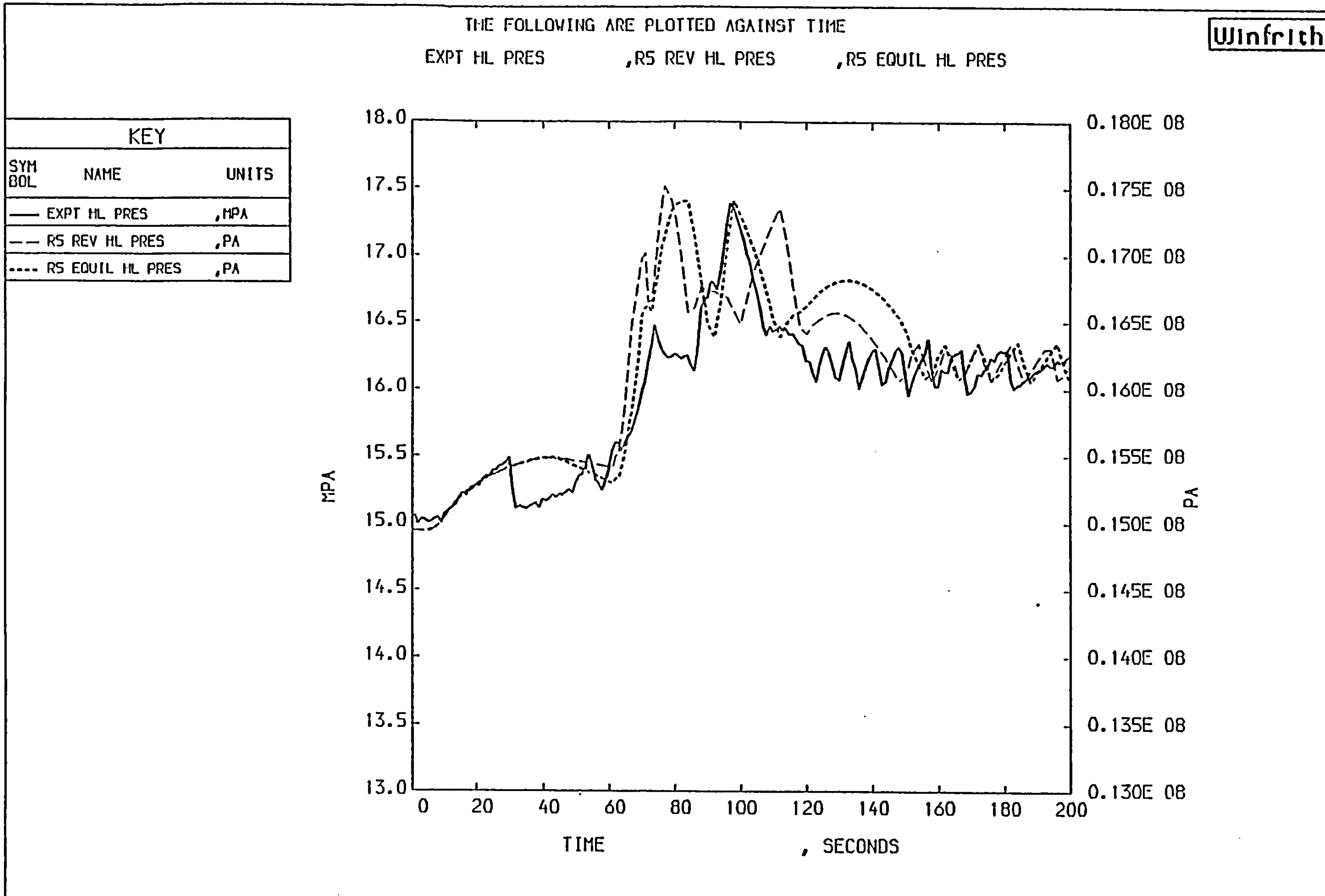

Figure 26. L9-3 HOT LEG PRESSURE - EFFECT OF EQUILIBRIUM

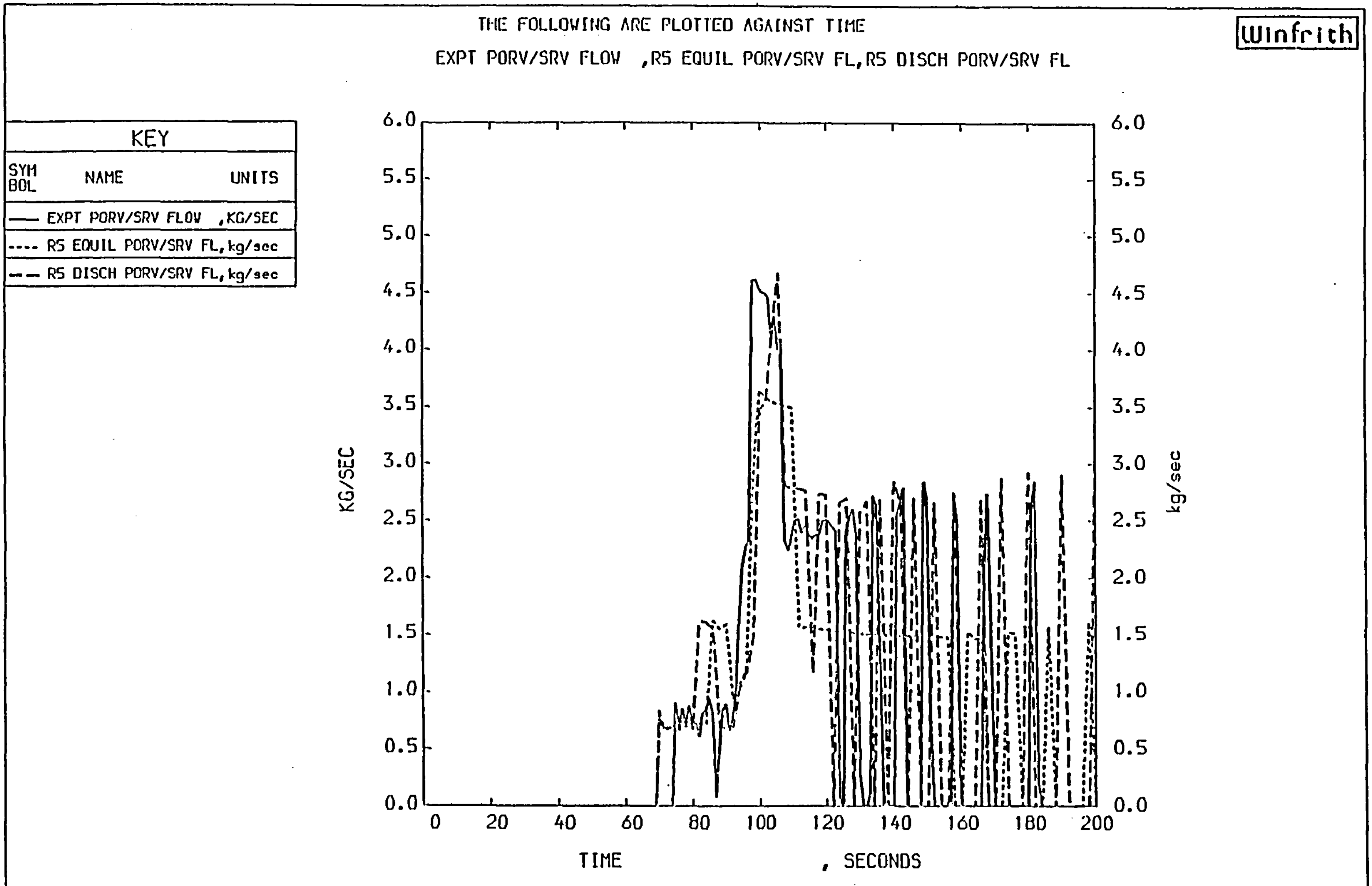

Figure 27. L9-3 RELIEF LINE FLOW - EFFECT OF INCREASED DISCHARGE

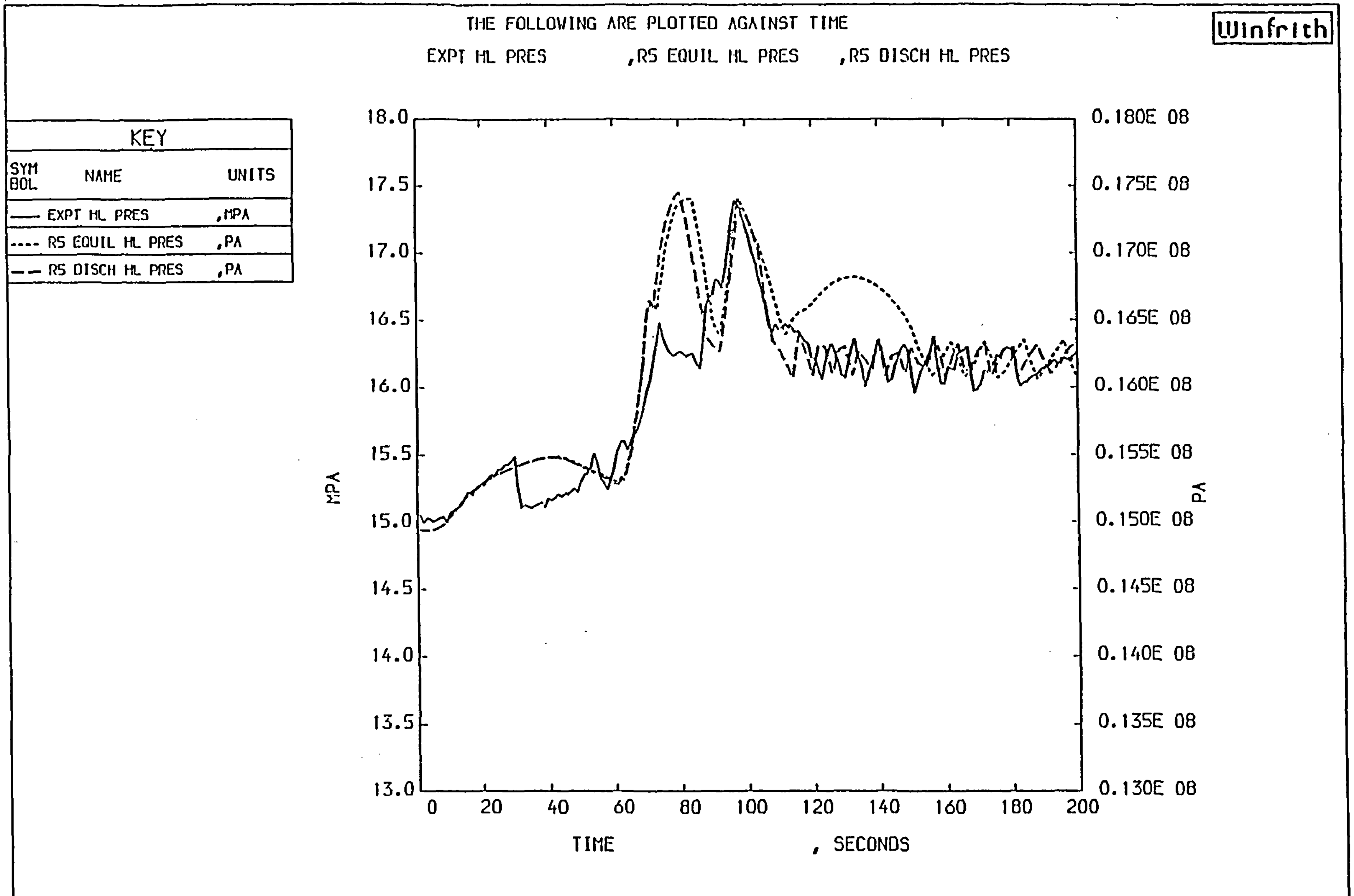

Figure 28. L9-3 HOT LEG PRESSURE - EFFECT OF INCREASED DISCHARGE

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Washington, DC 20555

10. SUPPLEMENTARY NOTES

11. ABSTRACT *(200 words or less)*

An analysis has been performed of LOFT Experiment L9-3, a loss-of-feedwater anticipated transient without trip, in order to support the validation of RELAP5/MOD2.

Experiment L9-3 exhibited a rapid boildown of the steam generator, following the loss of feed, with the reactor remaining close to its initial power until the steam generator tubes became sufficiently uncovered for primary to secondary heat transfer to be significantly reduced. The ensuing heat up of the primary fluid resulted in a reduction in power induced by the moderator feedback. The primary system pressure increased to the safety relief valve setpoint, before the fall in reactor power allowed the mismatch between primary system heat input and heat removal via the steam generator to be accommodated by cycling of the pilot operated relief valve (PORV).

Comparison between calculation and data shows generally good agreement, though with discrepancies in some areas. Weaknesses in the code's treatment of interphase drag and in the representation of the pressuriser spray are indicated, although a shortage of definitive data, particularly in the steam generator, may also be a factor. The overprediction of interphase drag led to a tendency to underpredict the initial inventory in the steam generator and also, perhaps, to overpredict the steam generator heat transfer while the tubes were being uncovered. There is indication that the pressuriser vapour region conditions were close to equilibrium during spray operation. The point kinetics model in RELAP5/MOD2 proved a viable means of representing the power history for this transient.

12. KEY WORDS/DESCRIPTORS *(List words or phrases that will assist researchers in locating the report.)*

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