TECHNICAL NOTE SRSC N° 87.96

FISSILE SOLUTION CRITICALITY ACCIDENTS

Review of Pressure Wave Measurement Experiments in the SILENE Reactor

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ABSTRACT

This document summarizes the experimental results obtained in the SILENE test reactor on pressure waves accompagnying fast power transients. Measurement data from a pressure sensor in the fissile solution was used to determine the relation between the maximum pressure wave amplitude Δp and certain characteristic parameters of the first peak : ω (the reciprocal of the period) and $\hat{E}$ (the energy integrated up to the maximum of the pressure peak).

The results indicate that the pressure signal is initiated prior to the maximum of the power peak ; it is very likely that the radiolysis gases contribute negative reactivity to the excursion kinetics, compounding the temperature effect.

On the basis of theses findings it may be affirmed that a significant pressure wave would only be generated during a fissile solution power excursion if the phenomenon occurred very quickly (i.e. in less thant 10 msec).

CRITICALITY ACCIDENTS IN SOLUTION

Review of Pressure Wave Measurement Experiments in the SILENE Reactor

1. EXPERIMENTAL OBJECTIVES

Several specific experiments were conducted during 1980 and 1981 in the SILENE reactor [1] to provide fundamental information on the mechanisms by which a dynamic pressure wave in produced in the fissile solution during an accidental criticality excursion. A pressure sensor was placed on the fissile solution midplane, and data was acquired for the following purposes :

- First, as part of the safety studies for which criticality experiments are carried out at the Valduc Nuclear Research Center, to develop simple models correlating the pressure wave with the power excursion kinetics (period, power, energy, etc...) for practical application to safety analysis.

- Application of this model to the SILENE reactor itself to ensure that the core vessel can withstand high reactivity steps, as the maximum permissible pressure wave on the vessel wall is limited to 8 bars absolute.

- A longer term objective based on the results of radiolysis gas formation experiments [2] is to understand and model the physicochemical phenomena governing the formation of radiolysis gases and the generation of a pressure wave.

These phenomena are important in nuclear safety since a pressure wave can jeopardize the integrity of the first containment barrier ; hydrogen formation due to radiolysis may result in an inflammation or explosion hazard ; and accurate modeling of an accidental criticality excursion in a fissile solution [$UO_2(NO_3)_2$, $Pu(NO_3)_4$, UO_2F_2] is only possible if the computer code set allows for radiolysis and bubble formation.

This is obviously a long term objective. Models were proposed in the USA as part of the KEWB program, and can constitute the groundwork for further research.

The work accomplished by the CEA/IPSN/SRSC to date and reviewed in this document has been limited to conducting tests with the SILENE reactor to develop simple models.

2. SILENE REACTOR CONFIGURATION AND DESCRIPTION OF EXPERIMENTAL DEVICE

SILENE is a uranyl nitrate solution fueled reactor with the feature to perform power transients corresponding to kinetics representative of an accidental criticality excursion.

The bottom of the core vessel includes a CEC BELL pressure sensor designed to ensure at all times that the reactor operating pressure limit of 8 bars absolute has not been exceeded.

For the purposes of this study a different type of pressure sensor (KISTLER) was placed in fissile medium on the solution midplane at the point of maximum axial flux (figure 2).

The CEC BELL pressure sensor is a tight wire design, while the KISTLER sensor is a piezoresistive model. The nature of the environment made the choice of a pressure sensor difficult : it had to be temperature-independent , acid resistant, relatively insensitive to nuclear radiation and with a minimum response time. Further details are provided in reference 3

3. EXPERIMENTAL RESULTS

The principal results are indicated in table 1. Figures 3 through 19 show the sensor values recorded during the power transients. The following notation is used throughout :

C_{U_t} Total uranium concentration ($g.l^{-1}$) (92,7 % ^{235}U enrichment)
V_f Final volume (l)
K_{eff_1} Effective reactivity at the moment of the first peak
T_2 Doubling time (msec)
ω Reciprocal of period (sec^{-1})

$\dot{E}$ Maximum power at top of first peak (fissions.sec^{-1})
$\hat{t}$ Time corresponding to maximum power during first peak
t_0 " " to beginning of pressure signal in the solution
t_p " " to maximum pressure signal in the solution
Δp Dynamic pressure wave at bottom of core vessel during first peak (relative value)
$\hat{E}$ Energy integrated to $\hat{t}$ (time of maximum power).

4. PROPOSED RELATION FOR Δp IN LIQUID PHASE

In compliance with the formalism defined in reference [3] the results were used to determine the following expression relating Δp (the relative pressure variation) to the power excursion parameters :ω(reciprocal of the period) and $\hat{E}$ (energy integrated up to the instant of maximum power) :

$$\Delta p \text{ (bars)} = 1.14 \times 10^{-19} (\omega \hat{E} - 6.2 \times 10^{17})$$

where ω = 1/Te (sec^{-1}) and $\hat{E}$ is expressed in fissions, as shown in figure 20).

5. INITIAL CONCLUSION

Theses experiments have provided us with a simple model that can be used for safety analysis purposes to estimate the amplitude of the pressure wave liable to be generated during a power excursion, for example to ensure that the result does not jeopardize the integrity of the solution vessel.

The expression relating Δp to ω and $\hat{E}$ clearly shows that the pressure wave depends both on the speed of the power transient characterized by ω (the reciprocal of the period) and on the energy released in the peak $\hat{E}$, i.e. the rate at which radiolysis bubbles are produced.

More concretely, graph No 21 plots the evolution of the pressure wave Δp versus the power excursion doubling time T_2, and shows that a significant pressure wave only begins to appear in the fissile solution for doubling times shorter than 10 msec.

Another aspect is worthy of note. Some figures include signal variations from the fissile solution pressure sensor as well as from the core vessel bottom pressure sensor, revealing a time and amplitude lag between the two sensors that is not surprising in view of their positions and the wave propagation rate in the core medium. However, as only the lower sensor was previously available, it was always assumed that the pressure wave appeared after the power peak ; these results show that a major pressure field is created simultaneously with the power peak, and that it probably affects the kinetics of the peak. Table 1 indicates the times corresponding to the onset of the pressure signal t_0, the maximum pressure t_p and the power peak $\hat{t}$.

All recent hypotheses and theories assume that the radiolysis gases only appear after the first peak and that the latter is thus only limited by effects related to thermal expansion. The initial findings suggest that this is not the case, and show that the ultrasonic technique [2] used to detect the "radiolysis gas onset threshold" requires further improvement. This method assumes that the ultrasonic waves are disturbed as soon as bubbles appear in the fissile solution, and considers this instant as the onset of radiolysis gas formation. In fact, this method detects the appearance of bubbles which have already reached a certain size, i.e. after a period of growth or coalescence, since the bubble detection time measured in this way always occurs after the first power peak.

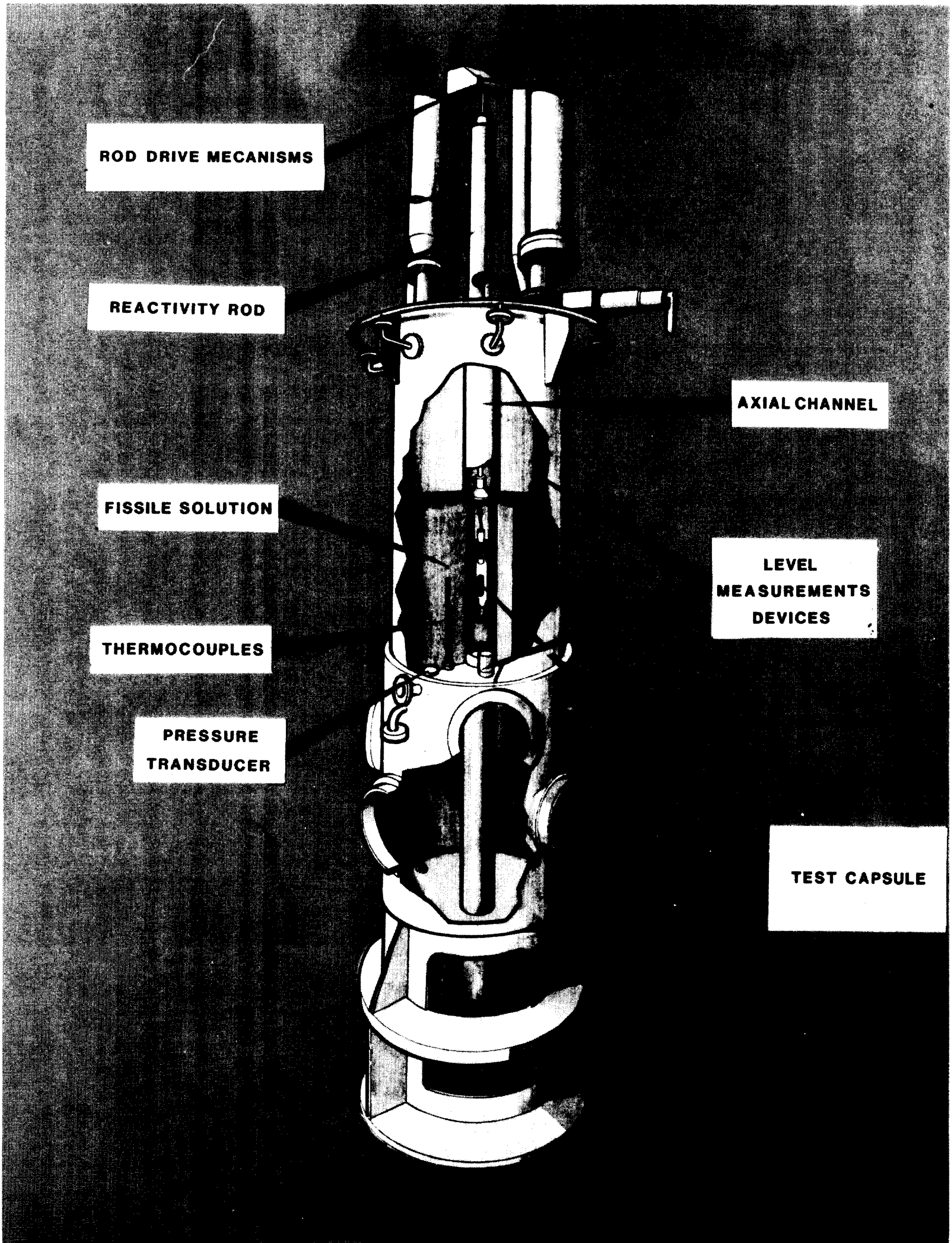
The pressure wave measured in theses experiments by the liquid phase pressure sensor thus incontestably provides the best representation of the pressure field created locally by the rapid appearance of radiolysis gas microbubbles which are not detected by the ultrasonic system until they have grown in size or coalesced with other microbubbles.

It is reasonable to assert that in the light of the results obtained with the SILENE reactor new models may be advanced to explain the physicochemical mechanisms governing the formation of free radicals by radiolysis along the paths of fission fragments, as well as the formation of microbubbles and their subsequent evolution (growth, coalescence, migration, etc...).

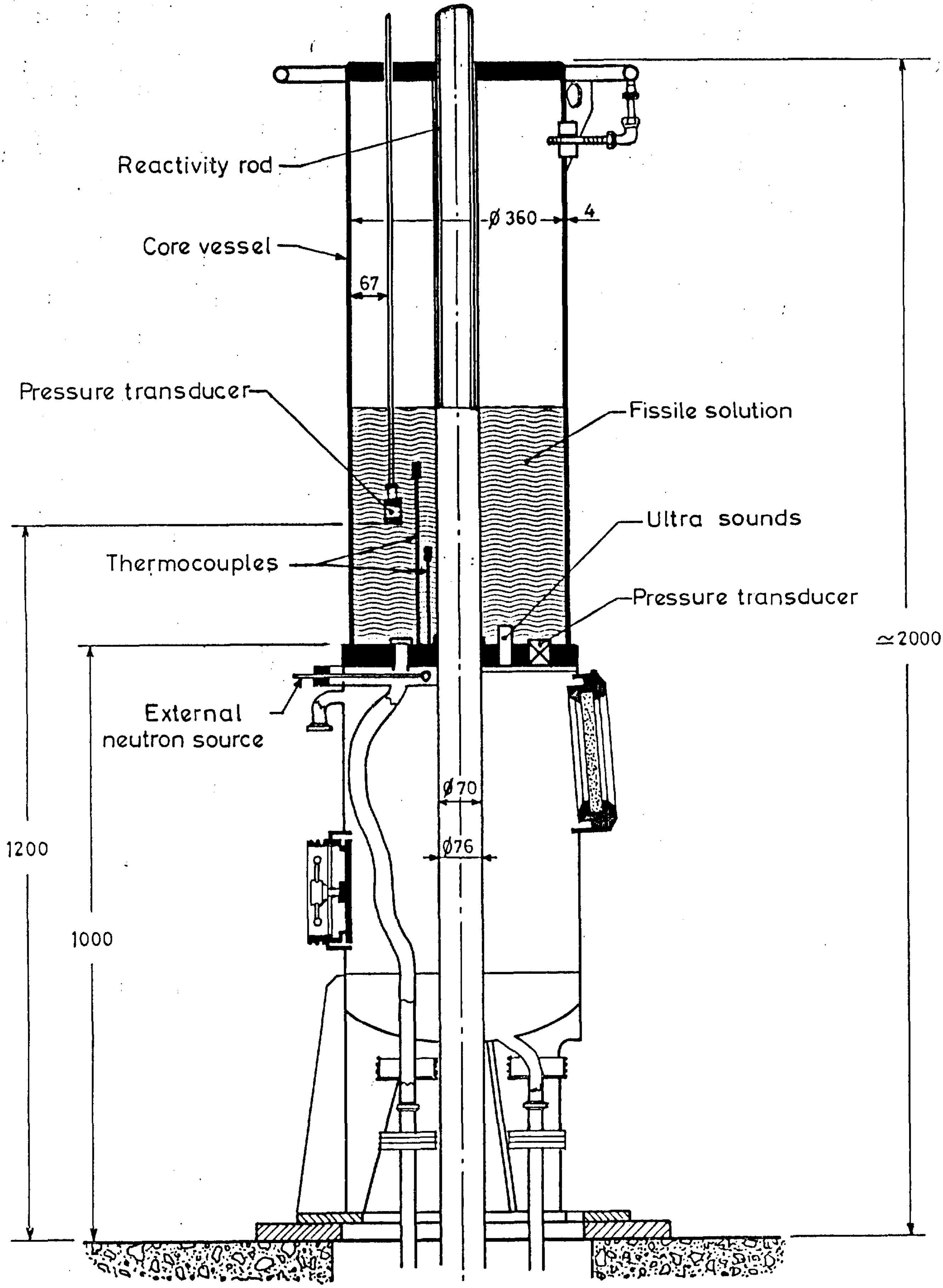
From a purely scientific standpoint it would no doubt be interesting to investigate what might be called the "fissile solution equation of state", but in comparison with the safety benefits the magnitude of the effort involved precludes any such project without the contribution of foreign partners interested in pursuing this area of research.

Configuration SILENE	experiment	$V_{f\ell}$	T_2 10^{-3} s	ω s^{-1}	$\dot{E}_{max}$ fission.s^{-1}	$\hat{E}$ fissions	Δp bars	$\Delta k_{eff} = k_{eff} - 1$ p.c.m	$	$\hat{t}$ 1er pic s	t_0 s	t_p s
lead shield C_{U_t}=61 g.l^{-1}	S1-152	39.46	2.3	301	1.63 10^{19}	8.83 10^{16}	3.22	1975	2.54	1.6285	1.618	1.6305
	S2-152	40.24	1.75	396	2.74 10^{19}	1.23 10^{17}	5.37	2350	3.02	1.3015	1.1940	1.3030
	S1-153	38.17	5.4	128	3.38 10^{18}	5.02 10^{16}	0.57	1290	1.66	1.585	1.568	1.594
	S2-153	40.50	1.56	444	3.32 10^{19}	1.27 10^{17}	6.35	2540	3.26	1.2025	1.1915	1.2040
unshielded C_{U_t}=71 g.l^{-1}	S1-169	40.42	2.2	315	1.38 10^{19}	7.55 10^{16}	2.7	1941	2.44	1.1205	1.1190	1.1230
	S2-169	41.01	1.8	385	2.11 10^{19}	9.47 10^{16}	4.17	2195	2.76	1.3245	1.3210	1.3265
	S3-169	39.43	4.3	161	3.88 10^{18}	4.6 10^{16}	0.64	1382	1.74	6.3400	6.342	6.3480
	S4-169	41.02	1.8	392	2.19 10^{19}	9.6 10^{16}	4.28	2195	2.76	1.3370	1.3355	1.3390
	S5-169	38.16	80	8,66	2.44 10^{16}	6.4 10^{15}	-	798	1.00	4.80	-	-
	S2-173	41.09	1.6	442	2.71 10^{19}	1.13 10^{17}	5.47	2370	2.98	1,2570	1.2550	1.2580

TABLE I



Cutaway view of SILENE REACTOR



"SILENE"

Experimental set up.

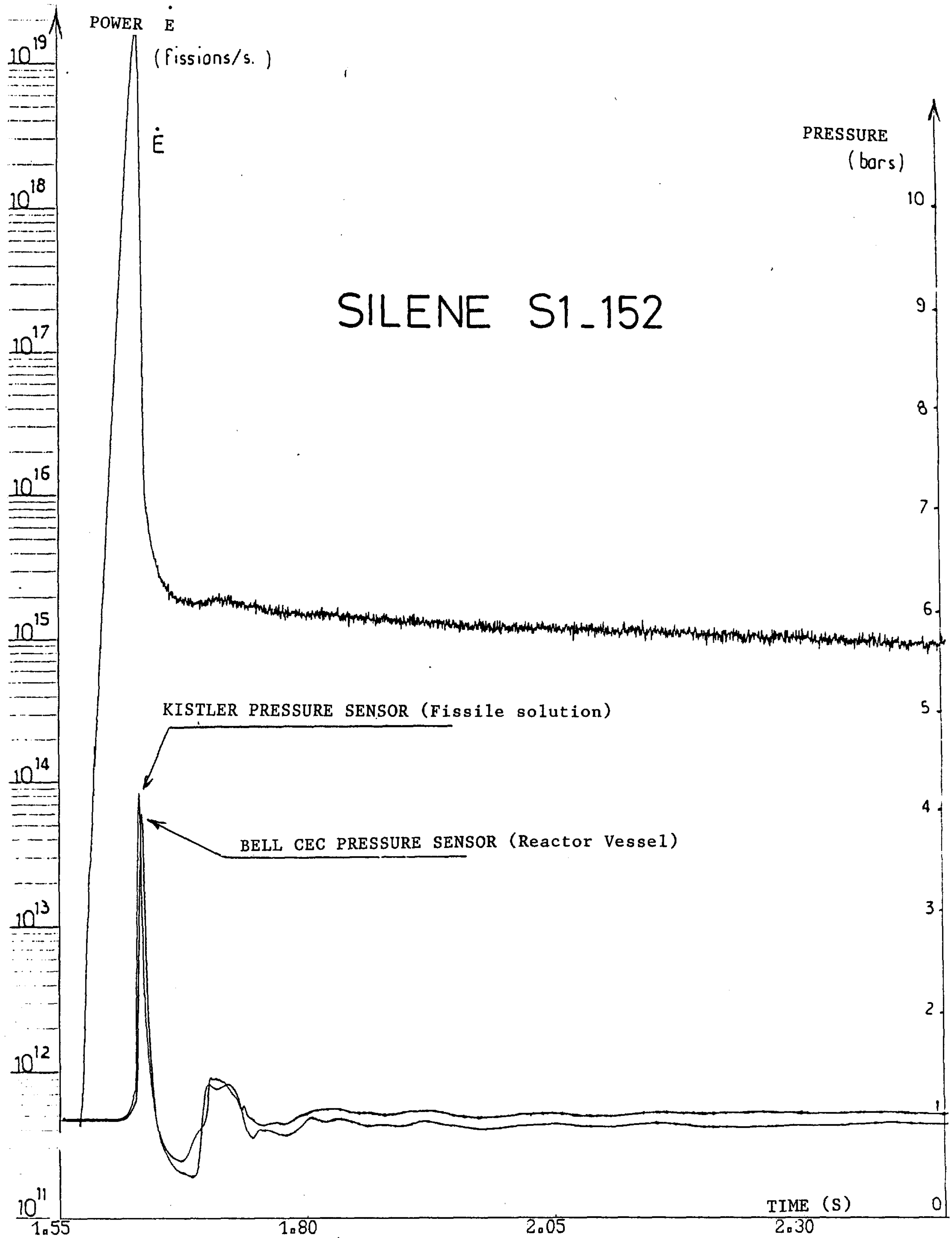


FIG. 3 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

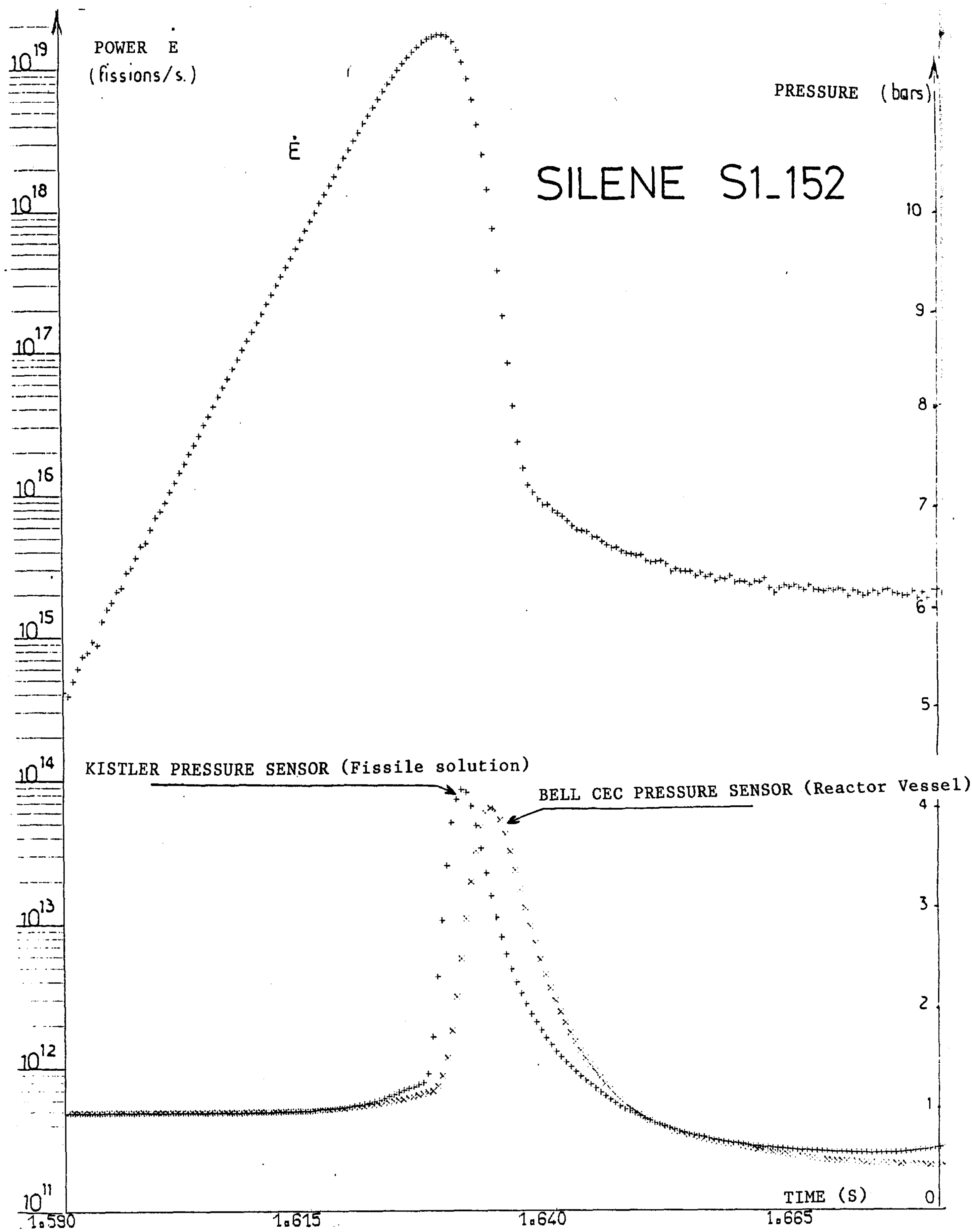


FIG. 4 -

SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

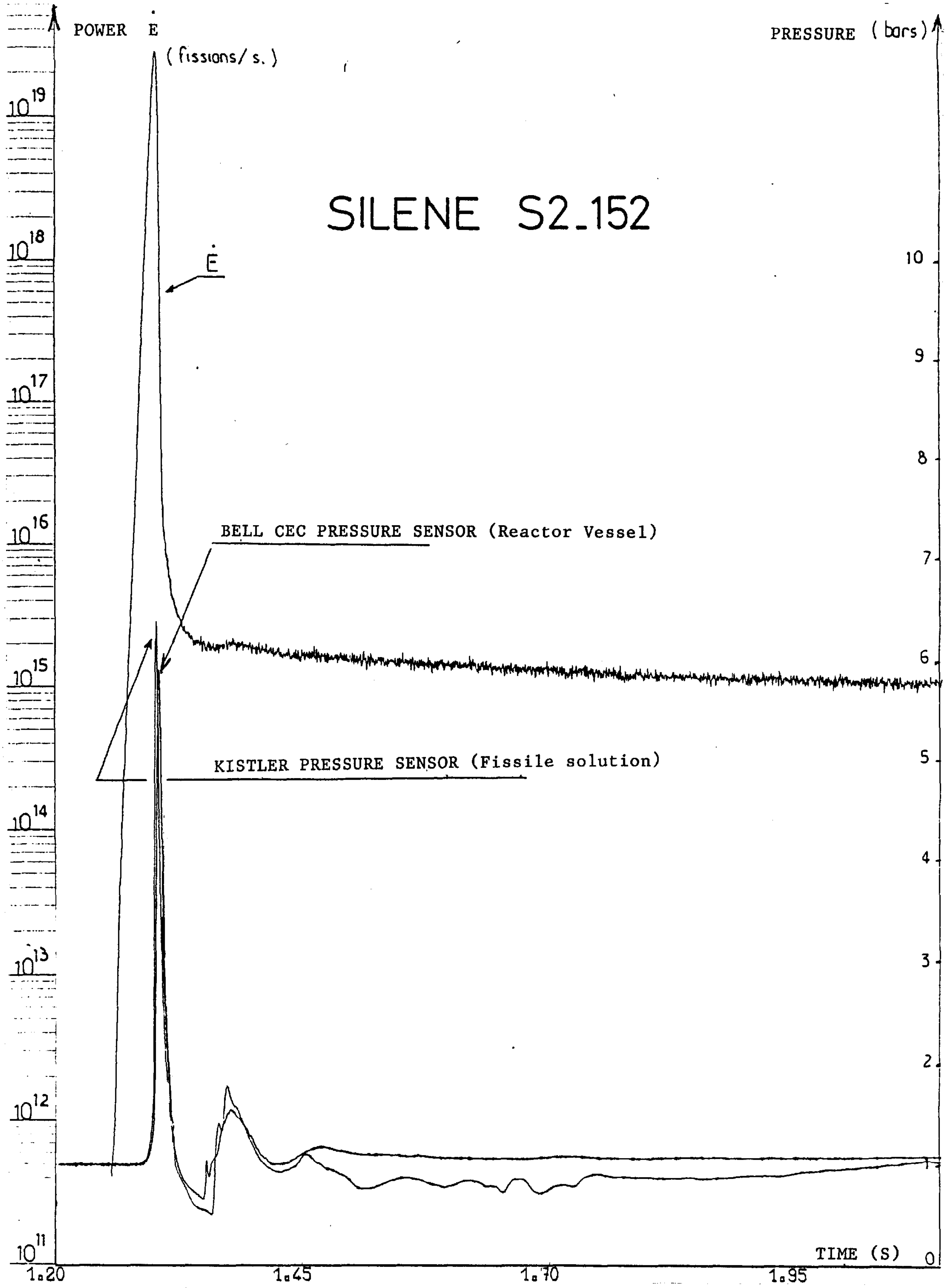


FIG. 5 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

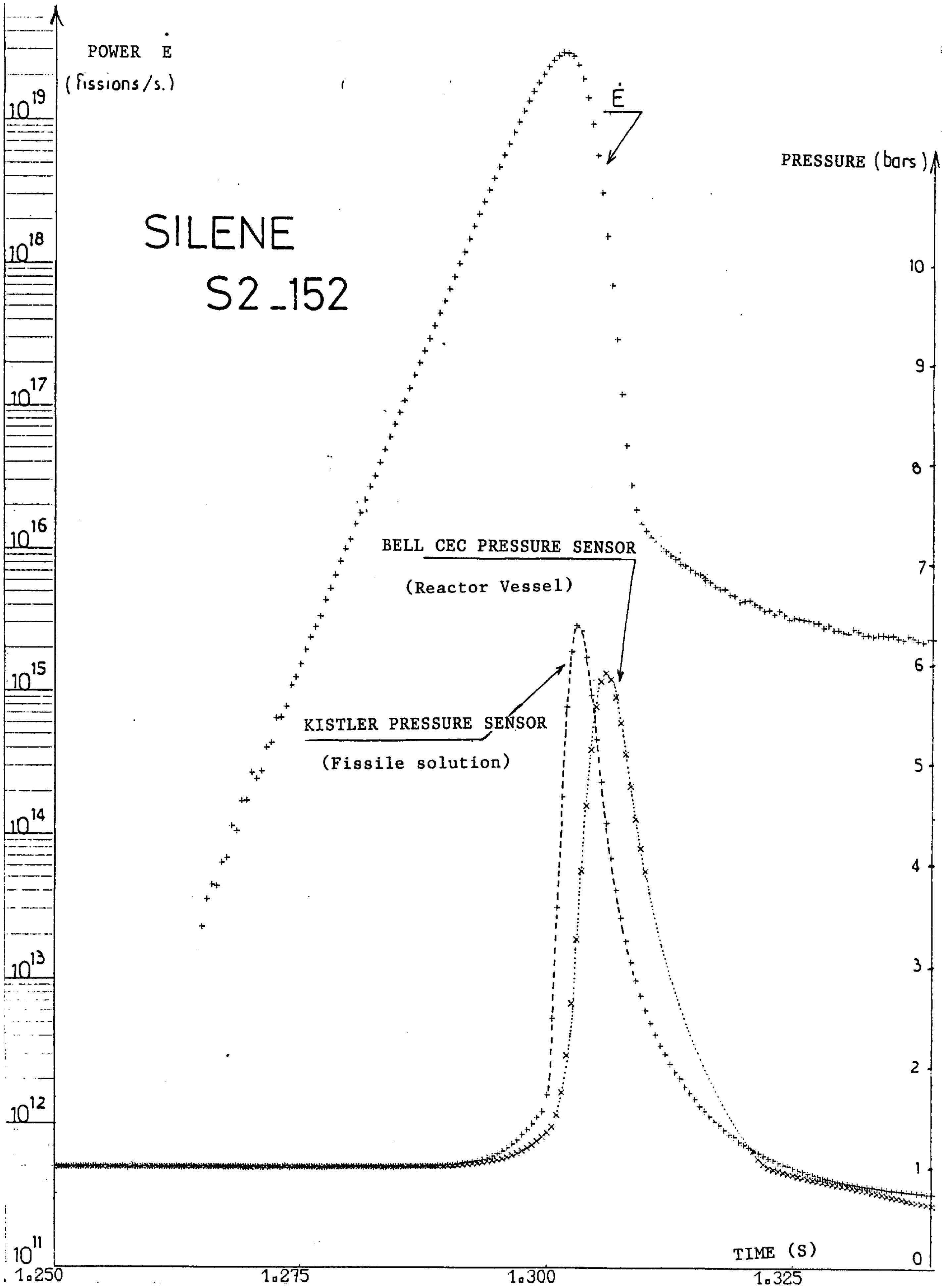


FIG. 6 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

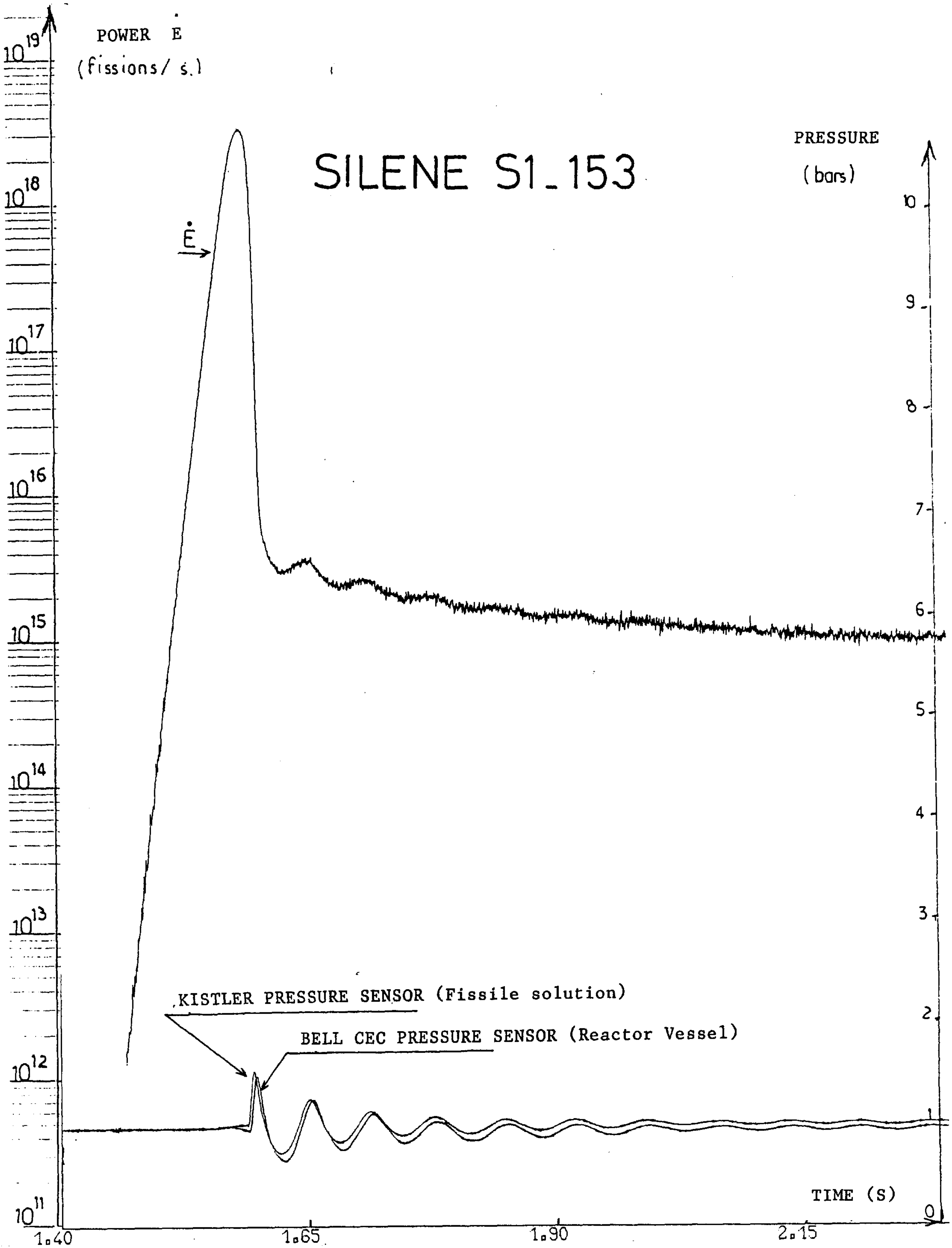


FIG. 7 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

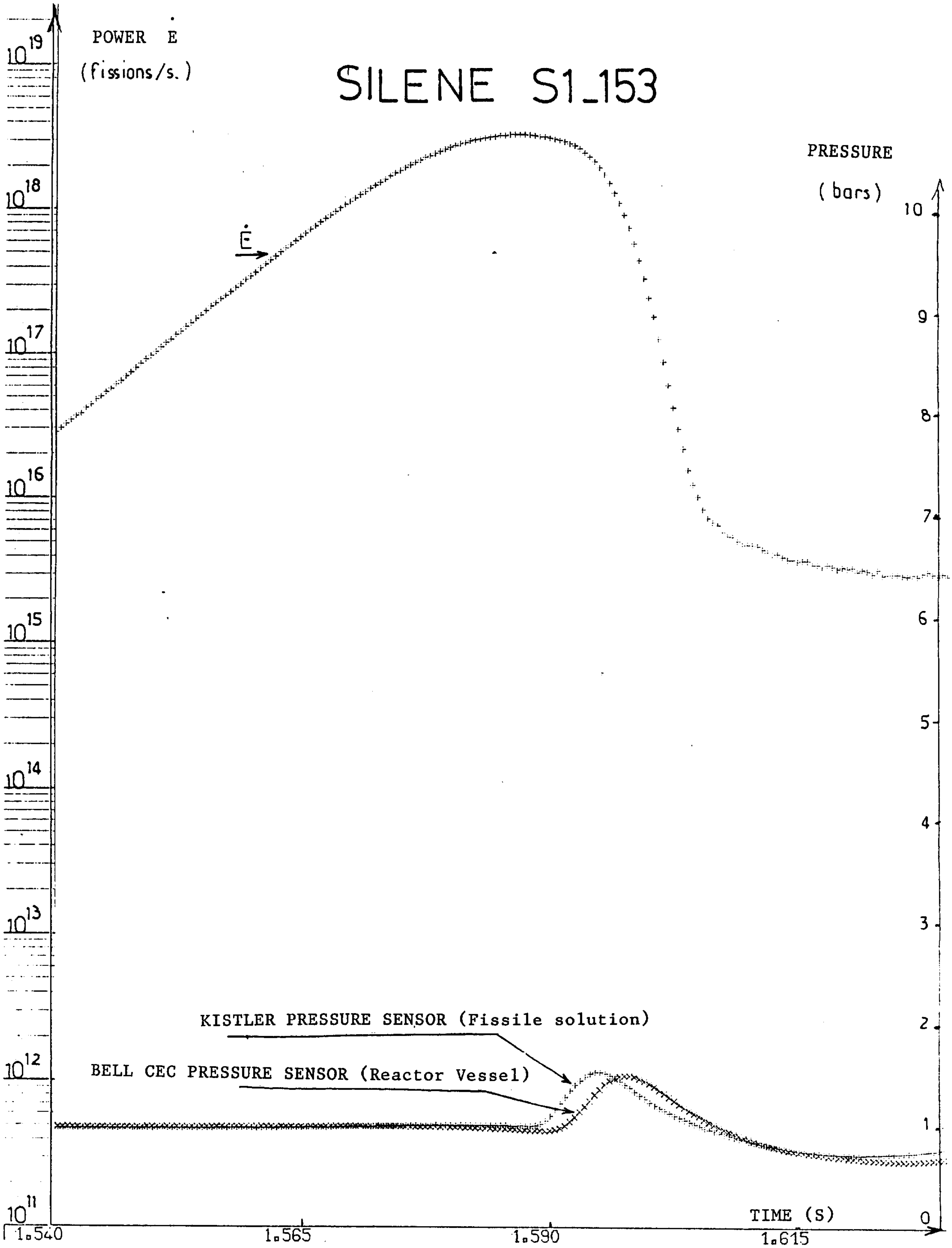


FIG. 8 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

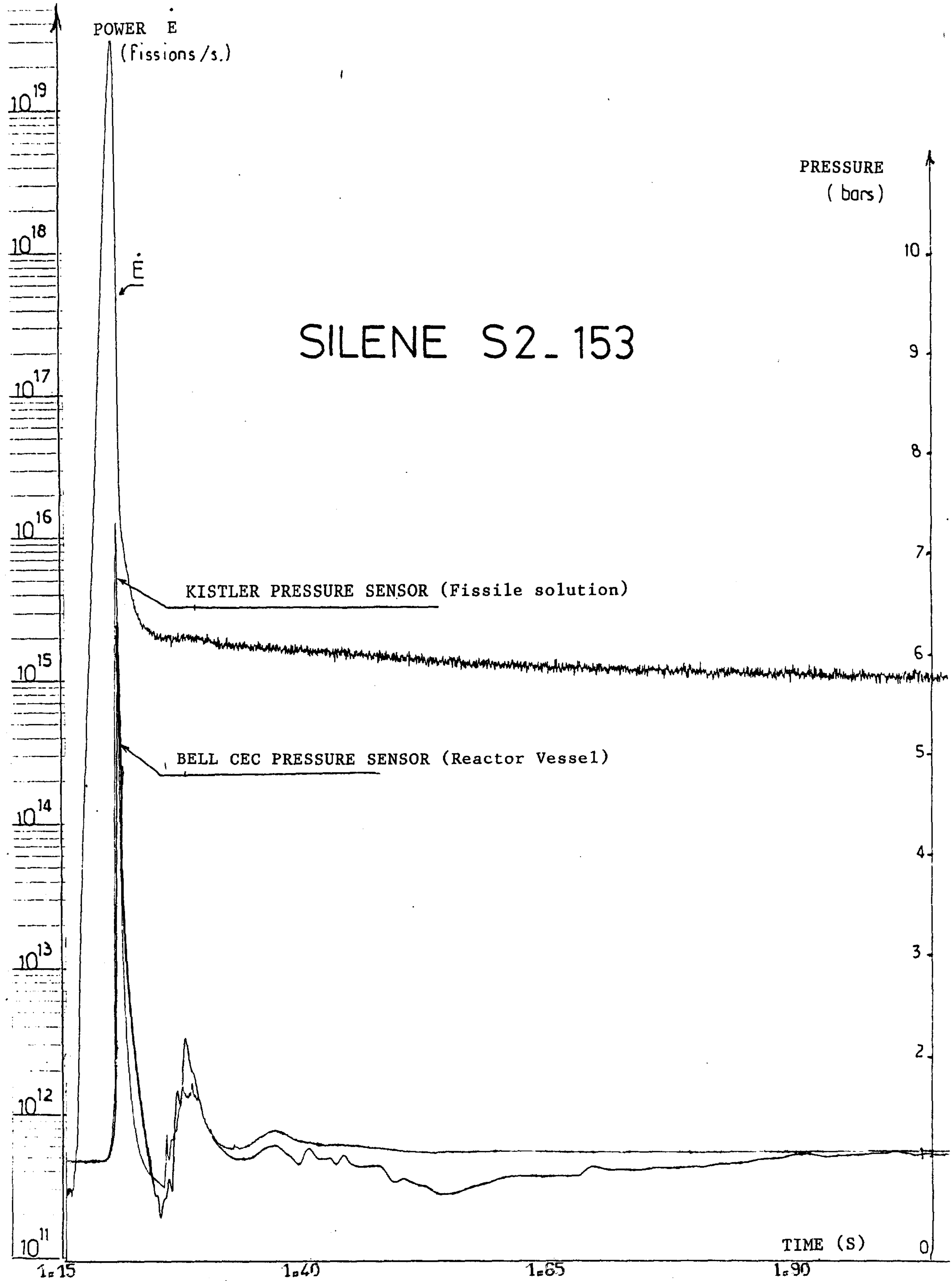


FIG. 9 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

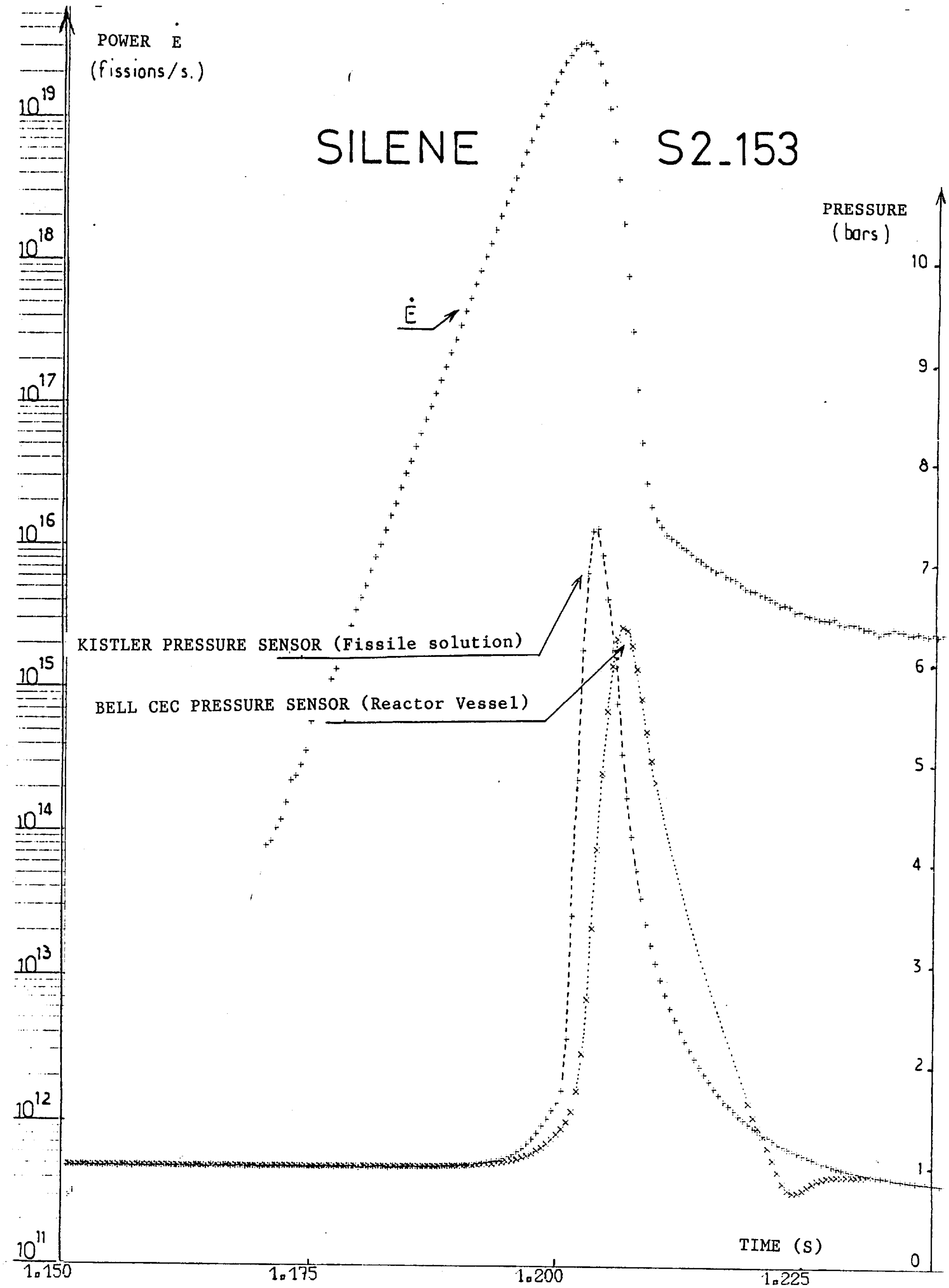


FIG. 10 - SILENE - Reactor POWER and PRESSURE SIGNAL RECORDING

. KISTLER Sensor in the solution

. BELL CEC Sensor at the bottom of the reactor vessel

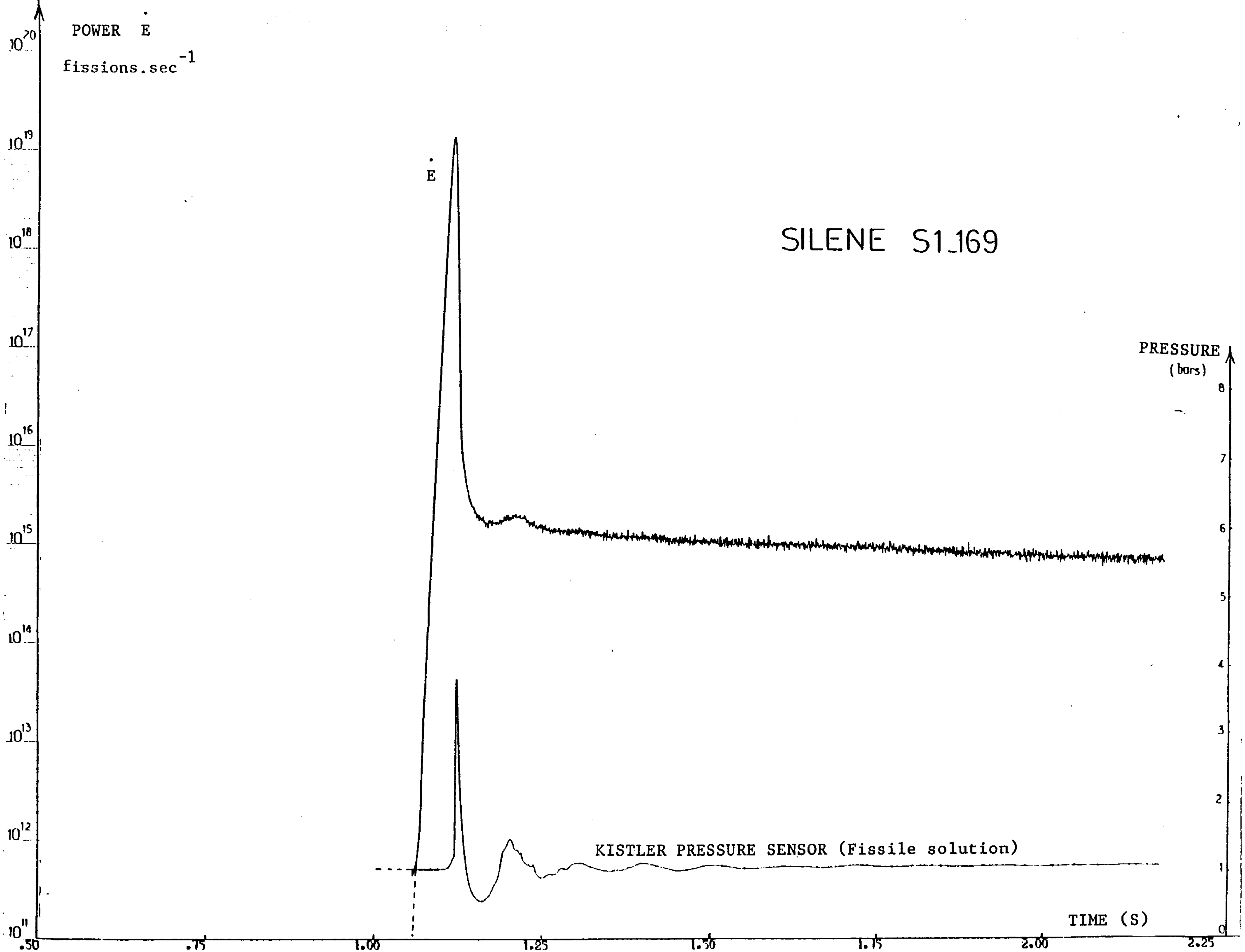


FIG.11 - SILENE - Reactor power and fissile solution pressure variations versus time.

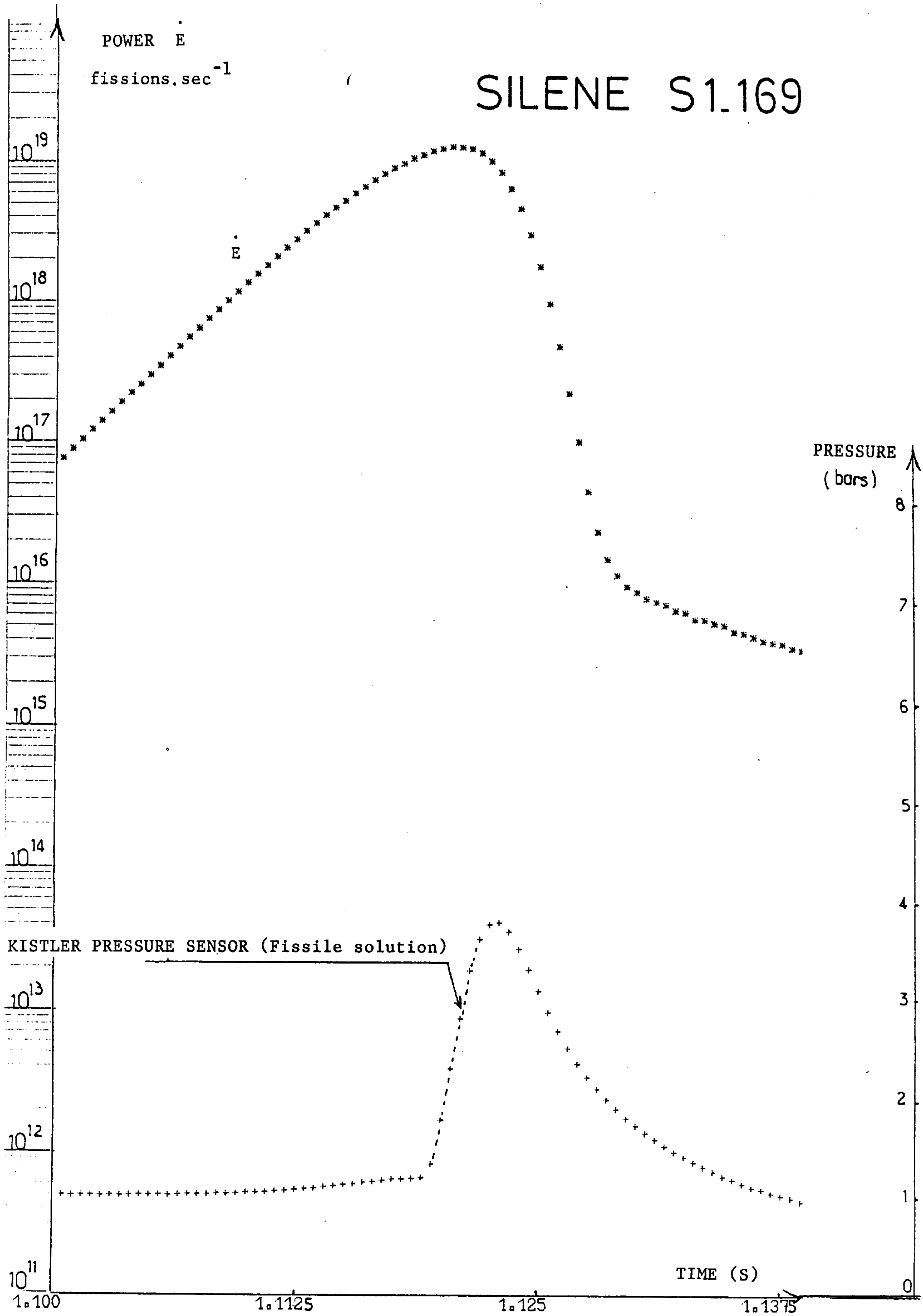


FIG. 12 - SILENE - Reactor power and fissile solution pressure variations versus time.

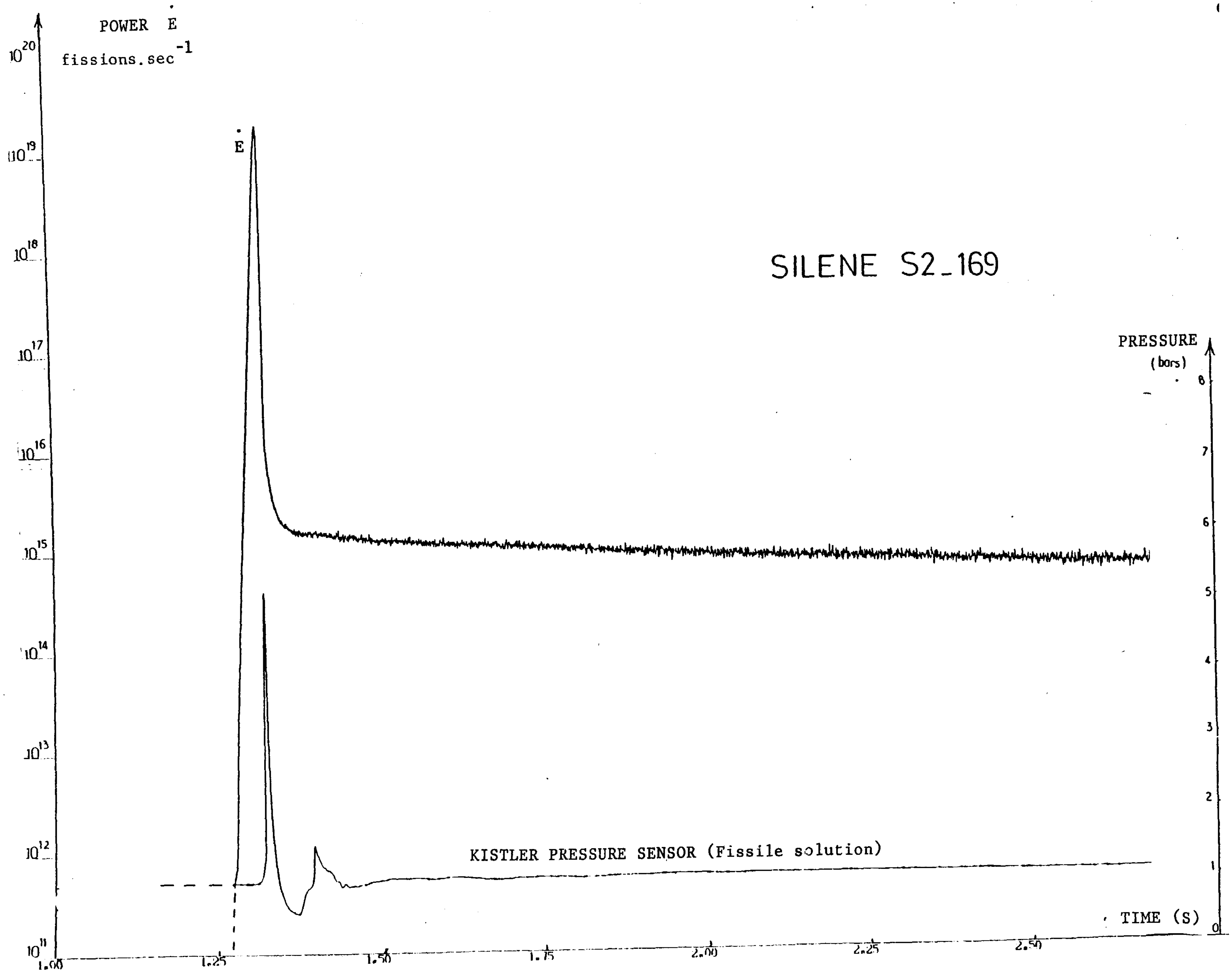


FIG. 13 - SILENE - Reactor power and fissile solution pressure variations versus time.

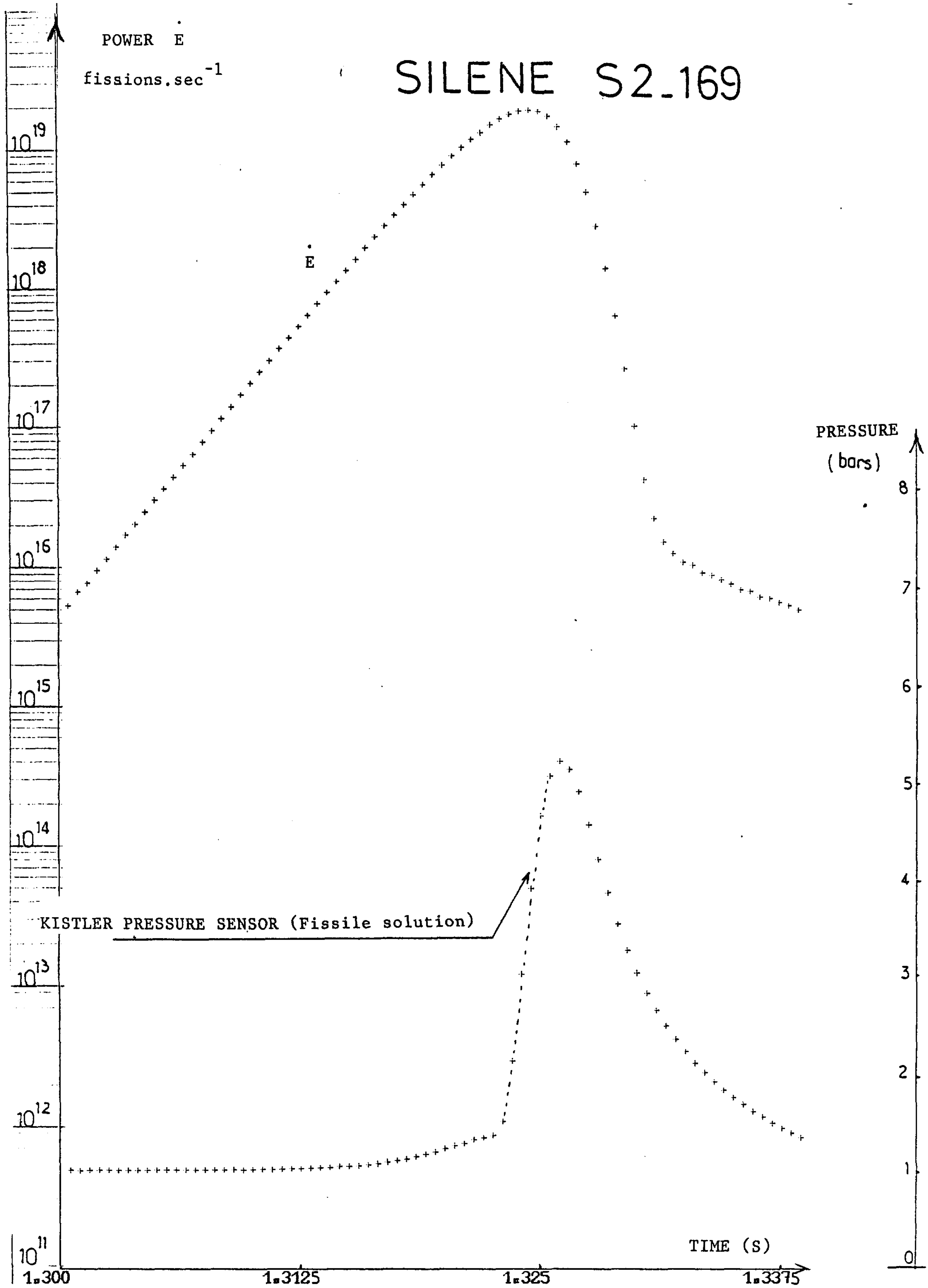


FIG. 14 - SILENE - Reactor power and fissile solution pressure variations versus time.

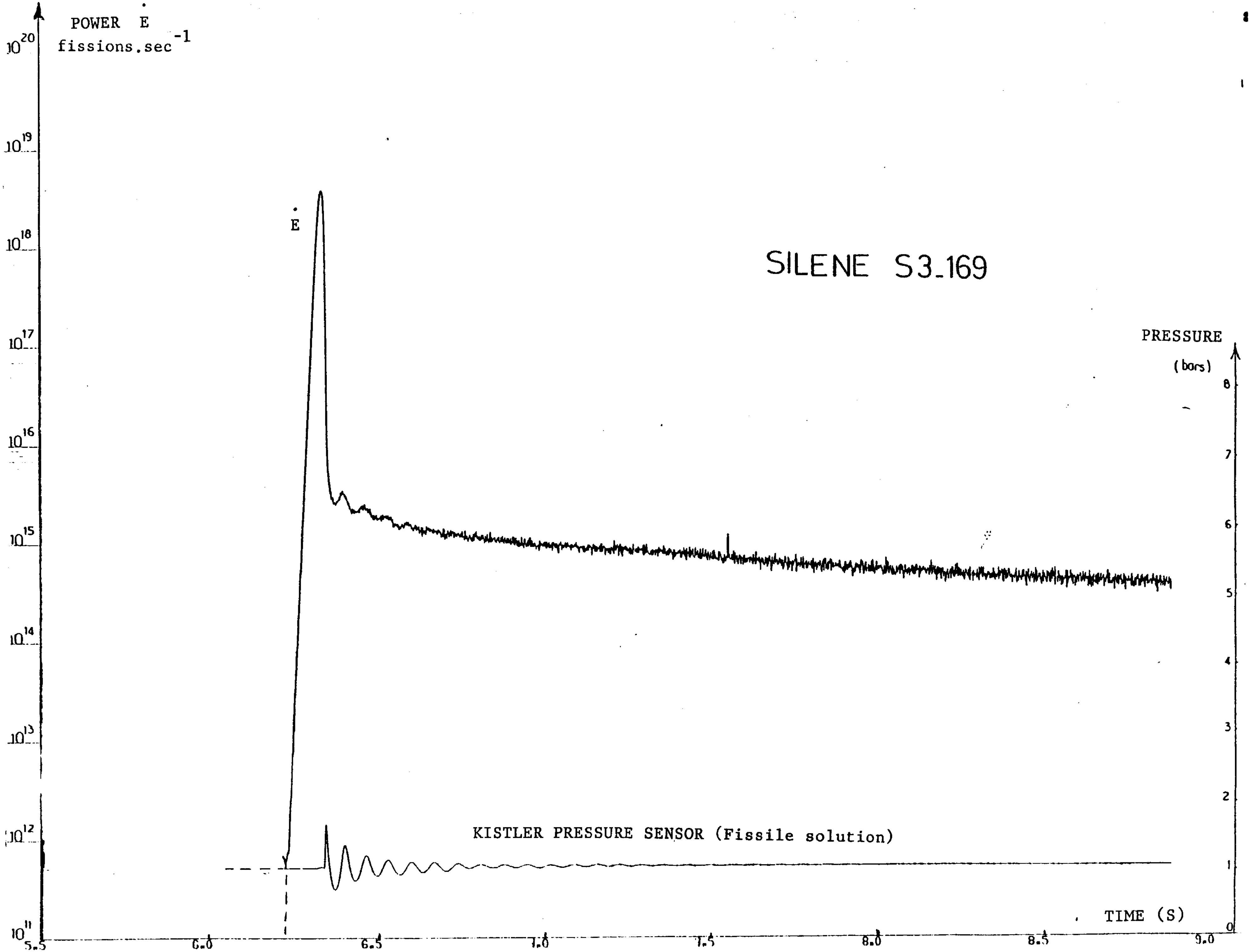


FIG. 15 - SILENE - Reactor power and fissile solution pressure variations versus time.

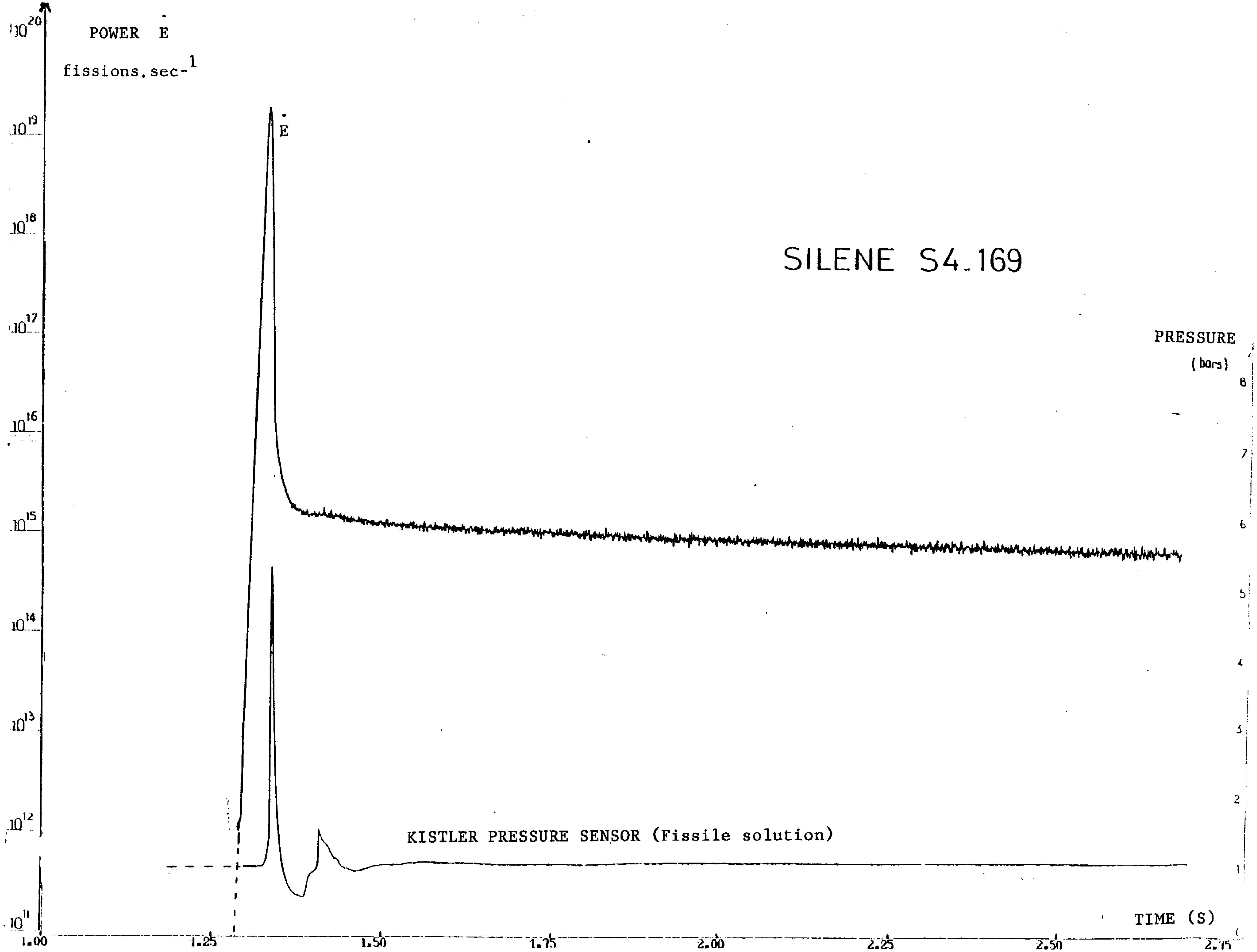


FIG. 16 - SILENE - Reactor power and fissile solution pressure variations versus time.

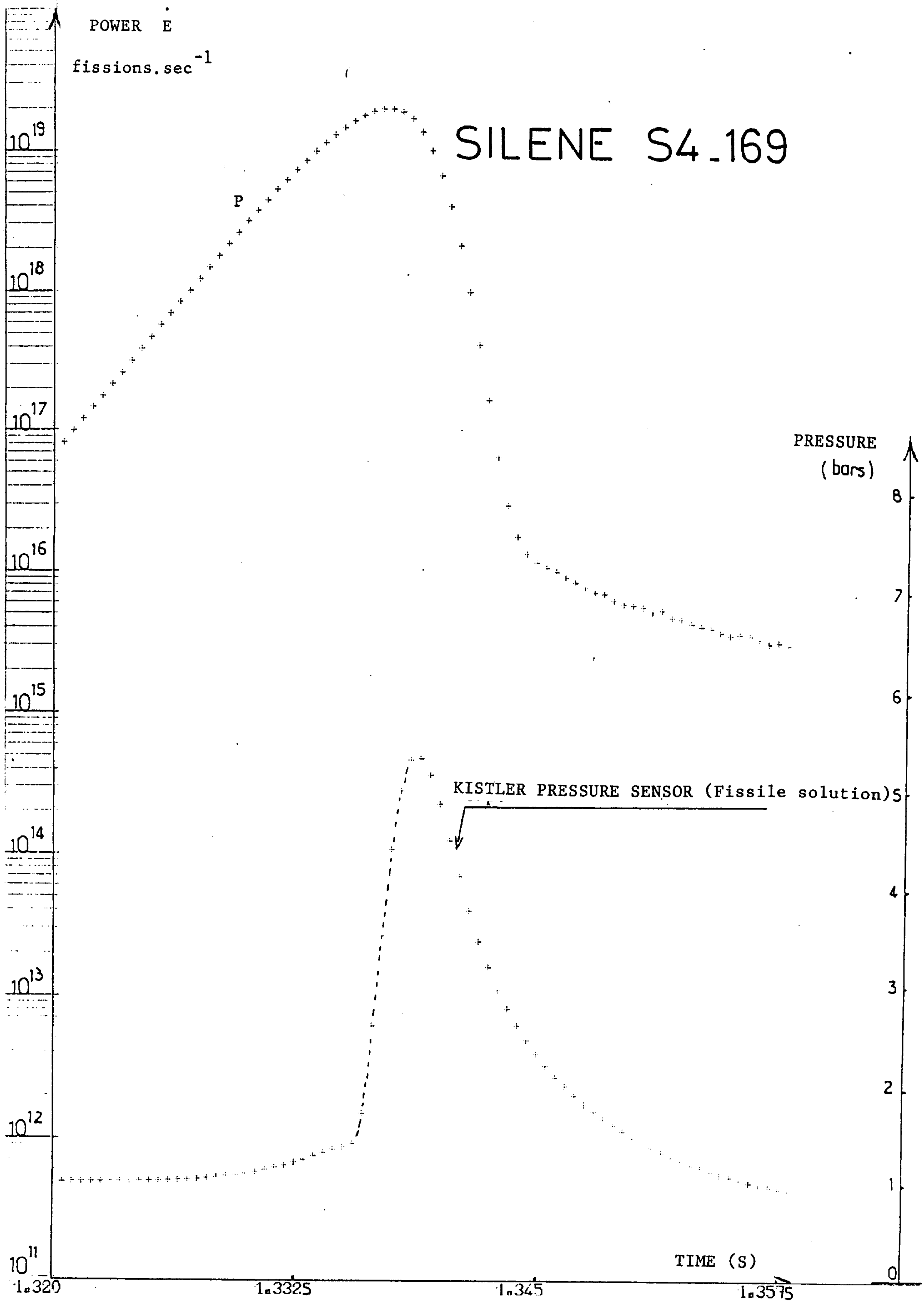


FIG. 17 - SILENE - Reactor power and fissile solution pressure variations versus time.

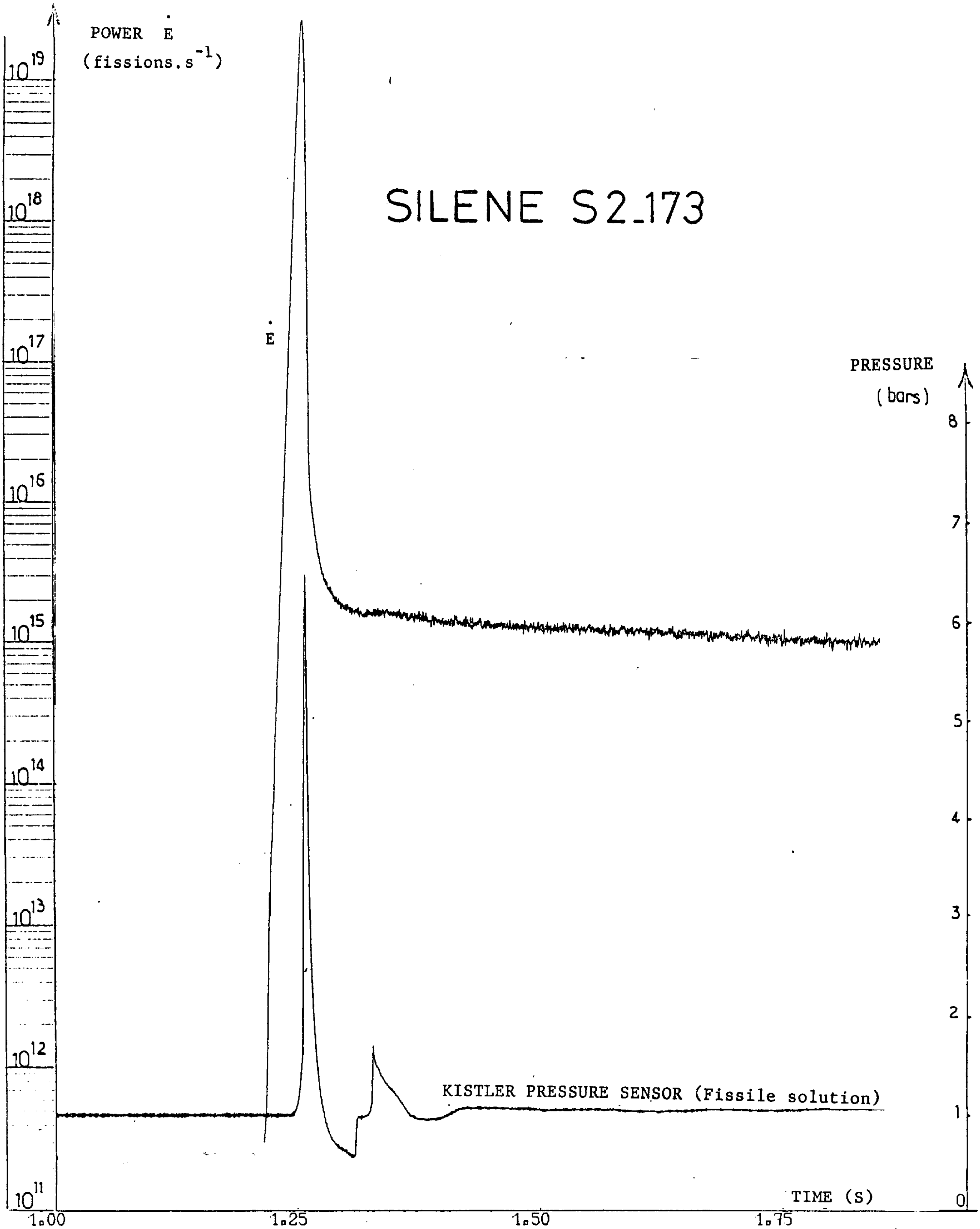


FIG. 18 - SILENE - Reactor power and fissile solution pressure variations versus time.

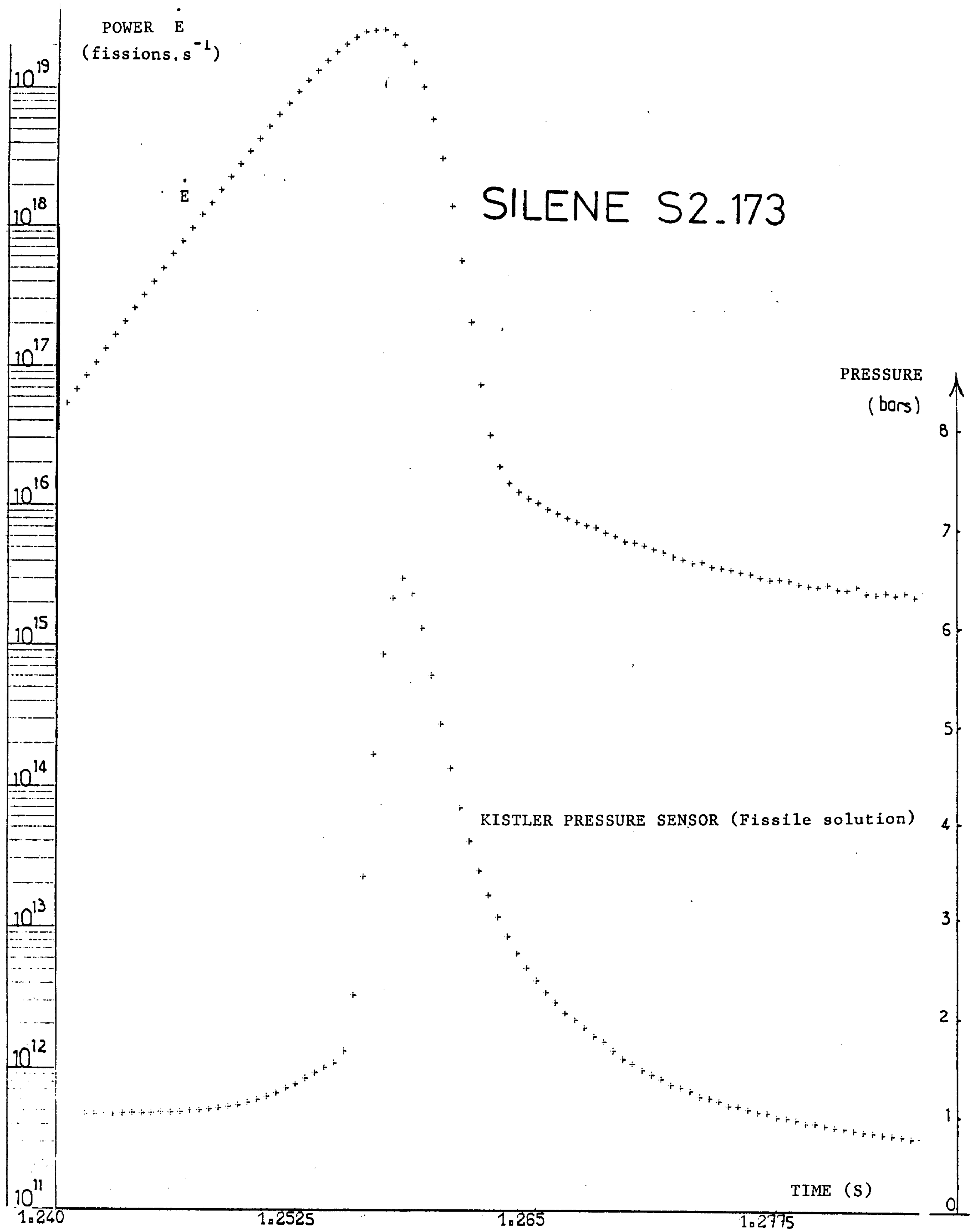


FIG. 19 - SILENE - Reactor power and fissile solution pressure variations versus time.

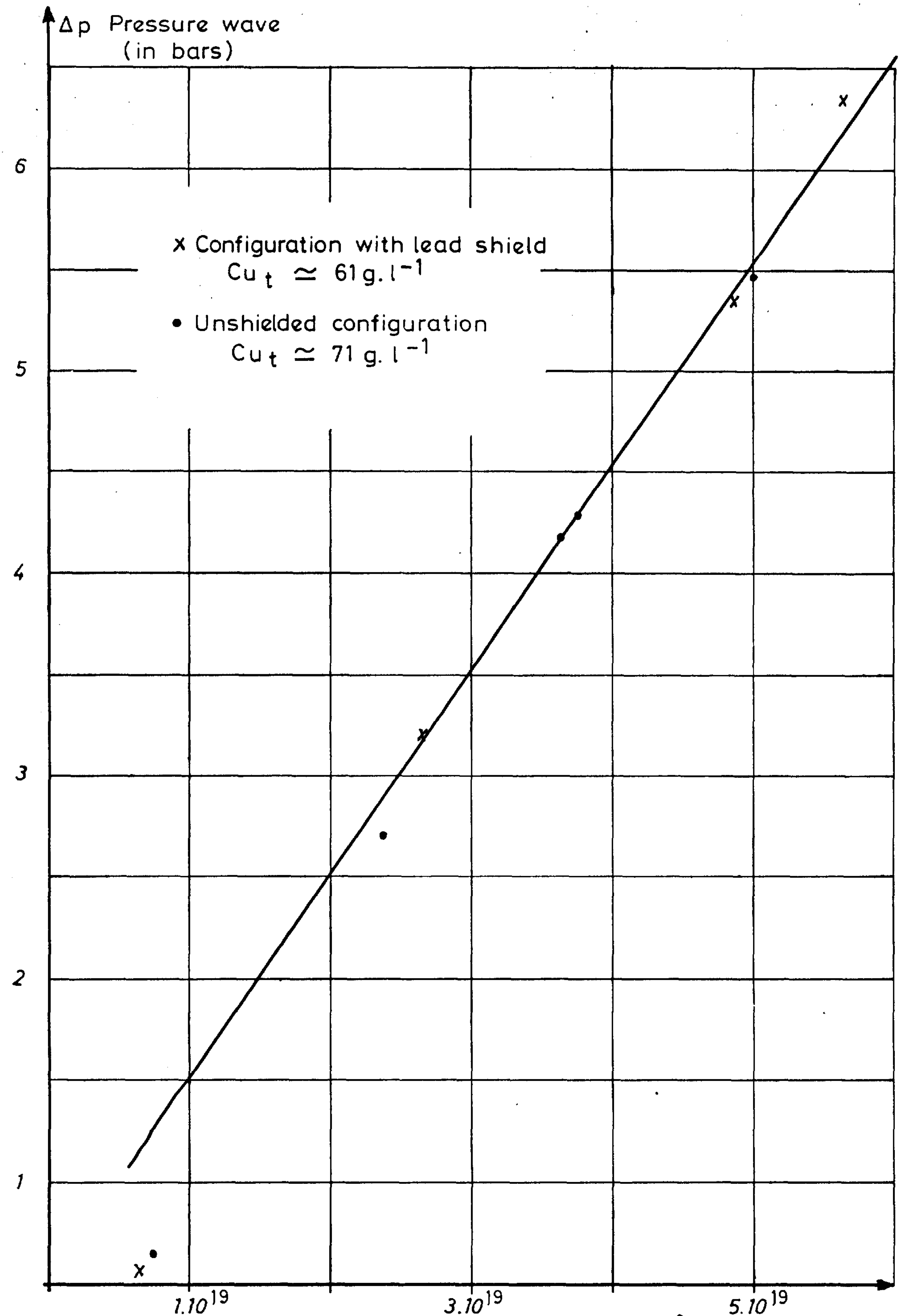


FIG. 20 : SILENE – $\Delta p = f(\omega \times \hat{E})$

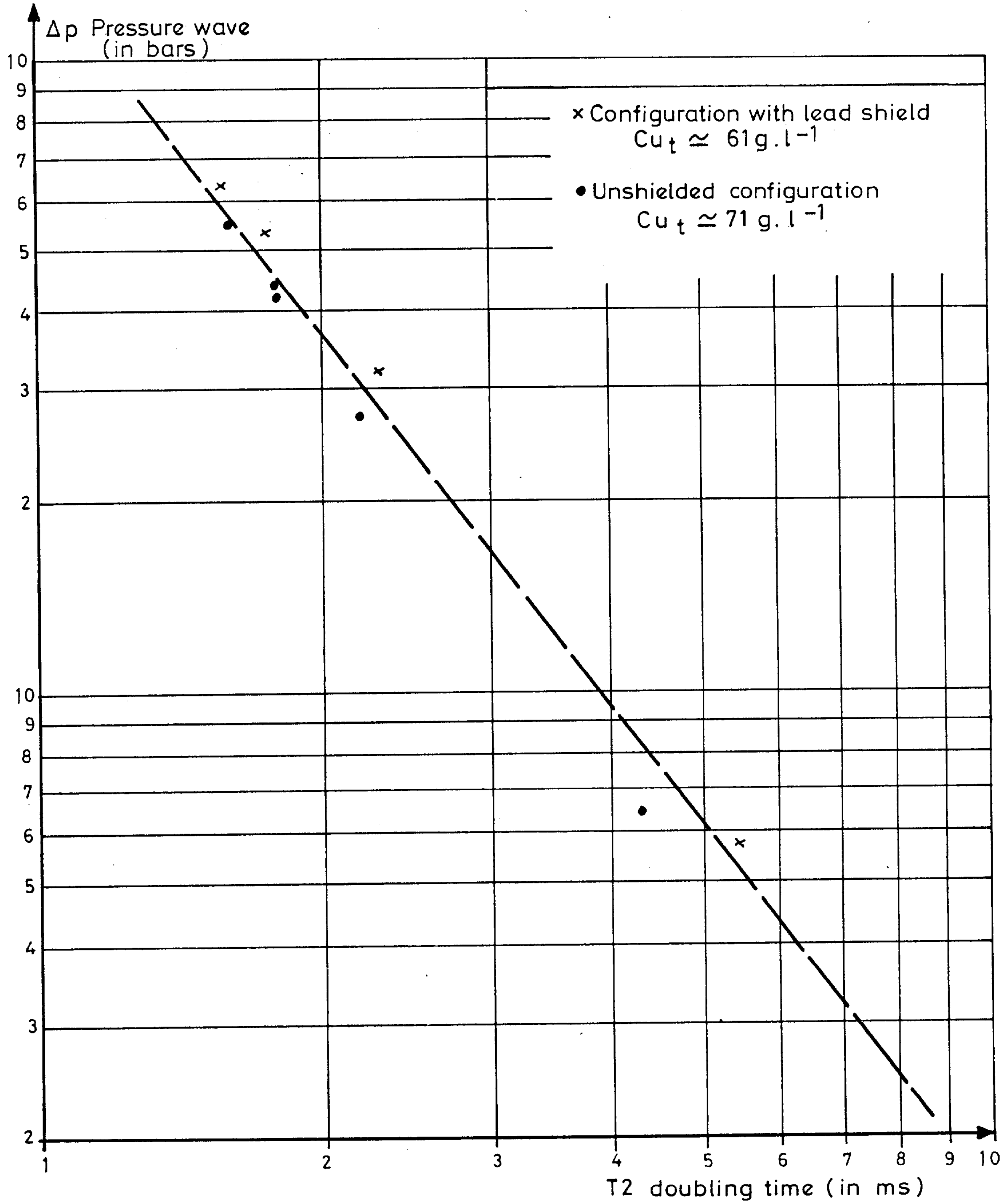


FIG. 21 : *SILENE_Pressure wave as a function of doubling time.*

R E F E R E N C E S

[1] - SILENE : A typical solution fueled research reactor
F. BARBRY - International Symposium on the use and Development of low and Medium flux research reactors.
MIT CAMBRIDGE (USA) oct. 1983.

[2] - Point sur les connaissances en matière de formation de gaz de radiolyse lors d'une excursion de criticité en solution.
F. BARBRY note technique SRSC N° 87.83 - février 1987

[3] - Etude et mesures d'ondes de pression au sein d'un milieu fissile divergent.
F. BARBRY - P. CENA - Note technique SRSC N° 21 mars 1980.