OPTICAL OBSERVATIONS OF ULTRA HIGH PRESSURE SODIUM ARC IN THE PERMANENT POWER FUSE

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ABSTRACT Solid sodium which is confined in a capillary in the PPF as a reusable current limiting material changes to high density vapour of the order of 3000 atm. due to Joule's heating by let-through fault current. Visual transients of phase change of sodium confined in a quartz capillary have been studied by means of a spectrometer and an image converter camera.

It has been revealed that phase change of sodium starts with the radiation of light when its enthalpy exceeds the value necessary for the boiling. According to spectroscopic studies, radiation of sodium is closely black body emission between 2000 and 5000 °K.

The plasma which develops in a capillary in the PPF has been profiled as a dense non-ideal plasma.

INTRODUCTION Permanent Power Fuse which is called by abbreviated name PPF is an entirely new reusable fuse with excellent current limiting performance developed by Mitsubishi Electric Corp., Japan. Since 1969, various PPF used devices have been applied to the actual field.(1)(2)(3). Principle of operation of the PPF is out lined below. The sodium which shows low resistance for a continuous current evaporates immediately on the flowing of a fault current establishing a high temperature and high pressure plasma with high resistivity. With abrupt change of the resistance of the sodium, the fault current is effectively limited. A piston is employed to control the pressure rise due to the expansion of the sodium and to provide the self-rehealing force to the expanded sodium by high pressure gas behind the piston.

Current limiting performance of the PPF depends greatly on supercritical properties of the sodium. In pre-arcing period of the PPF, phase transformation from solid to supercritical vapour develops within a few ms. Since little is known about the properties of supercritical vapour of the sodium, any qualitative information gives considerable contribution to establish the design basis of the PPF.

In this paper,

(1) processes of phase transformation, and

(2) the order of state variables of supercritical sodium vapour

are out lined on the basis of experiments made by a special model fuse with sodium element confined in a quartz tube.

(1) was profiled from estimation of electrical resistivity obtained from transients of voltage and current measurements and also from speed of vapourization observed by a image converter camera.

(2) was estimated by spectroscopic observations of the sodium arc. Temperature of the supercritical sodium vapour with radiation were estimated as the order of 4000 °K.

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The plasma in the PPF with such order of temperature and pressure belongs to dense strongly nonideal plasma (plasma for which the mean particle potential and kinetic energies are of the same order of magnitude), which has been studied by many scientists to get informations on the structure of the plasma, on the energy spectrum of the electrons and also on quantum mechanical phenomena peculiar to dense strongly heated media.(5) (6)(7) Any information obtained on the plasma in the PPF will give some additional knowledge of strongly nonideal plasma.

EXPERIMENTAL PROCEDURE

(i) MODEL PPF A quartz tube with inner diameter of d_o is O-ring shealed on both ends between copper terminals I and II as shown in Fig-1. Ar gas is filled at 10 kg/cm^2 behind the piston. Tests were made at d_o of 1 m/m. Radial emission of the sodium element was observed through the window of the model. Hereafter, the model PPF is abbreviated to PPF.

(ii) TEST CIRCUIT Fig-2 is a test circuit. The test circuit consists of a capacitor bank with total capacitance of 76000 μF charged to 100 to 400 V., inductance with 20 μH and controlled Thyristor to turn on short circuit current through the PPF. Tests were also made at capacitance of 16000 μF.

(iii) CIRCUIT CONDITIONS FOR THE TESTS Simplified skeleton circuit of Fig-2(a) is given in Fig-2(b). In Fig-2(b), the current through the PPF (denoted as N) and the parallel resistor R are denoted as i_1 and i_2, respectively. The voltage across the PPF is denoted by V_f. Fig-2(c) is a schematic drawing of a wave form of the current i_1 and i_2. The current through the PPF is transferred to the parallel resistor R after the abrupt increase of resistivity of the sodium element at i_c. In Fig-2(c), τ means the time for the current transfer from the PPF to the resistor. After the transfer of the current i_1 to R, the current i_f remains due to the voltage V_f. T_p means a pre-arcing period of the PPF. Process of the increase of the resistivity of the sodium element and streak observations have been investigated during $T_a + \tau$ under the circuit condition at C = 76000 μF keeping other conditions as given above. Spectroscopic observations for the plasma during $\tau + T_f$ have been made under the same circuit conditions of the capacity at C = 76000 μF. Spectroscopic observations have also been made for the plasma during τ by reducing the capacity of the capacitor bank to 16000 μF in order to diminish i_f or T_f down to be negligible. A resistor R connected in parallel with the PPF is employed to reduce the mechanical stresses impressed upon the quartz tube at the development of the high pressure plasma.(3) Voltage and current signals were derived to a computer aided digital data aquisition and analysis system.(4)

(iv) OPTICAL OBSERVATIONS Onset of light emission from the sodium element during pre-arcing period was detected by a photomultiplier (1P28).

Time resolved and time integrated spectroscopic observations were made by a spectrometer (GE-100 Shimazu, Japan) and a spectrographic dispersion unit (Model D2, Beckman-Whitley, U.S.A.) respectively. The time integrated record of spectra was made on photographic film (Kodak high speed film 2485). The dispersion unit covers wave length between 2000 to 10000 Å. The spectrometer (GE-100) is equipped with 3 channels of photomultiplier out puts. Each multiplier can be adjusted to arbitral spectral line which is selected among many lines because of its significance of

time resolved observations. Three traces of the multiplier out puts give time resolved records of the selected three lines.

The calibration of wave length dependence of the spectrograph including the films was done with a NBS standard lamp, and relative intensity calibrations of the arc spectrum through neutral filters of four different optical densities.

Axial speed of the development of vaporization of the sodium was observed by an image converter camera (IMACON, John Hadland).

RESULTS AND DISCUSSIONS

(i) FORMATION OF SODIUM PLASMA For the PPF with d_o of 1 m/m, resistivity was calculated from the measurements of voltage and current transients against energy input (Enthalpy) to a unit volume of the sodium as shown in Fig-3 by a solid line. In this case, the Enthalpy was calculated under the assumption that the temperature distribution of the element is axially and radially homogeneous during Joule's heating up to the point T and that heat conduction to the wall of quartz is negligible. In Fig-3, a dotted line is a theoretically calculated curve of resistivity. In the calculation, the resistivity vs. temperature curve which has been authorized up to a boiling point at atomspheric pressure is extrapolated to the boiling temperature of 1200 °C at 10 atm. This boiling point at 10 atm. is denoted as T in Fig-3. In Fig-3, each notation, S, SL, L and LV means phase of sodium, Solid, Solid + Liquid, Liquid, Liquid + Vapour, respectively. Zone of each phase is correspondingly related to Enthalpy axis. Point E in Fig-3 means that onset of light emission was detected by a photomultiplier at this point.

Experimental curve agrees well with the calculated curve up to point T. Homogeneous Joule's heating in these regions is experimentally supported. Homogeneity of the plasma up to the point T is also supported by the fact that the emission is not observed untill the point T.

Beyond the point T, calculation is made assuming that cylindrically symmetric core of vapourized sodium with resistivity of infinity grows radially. Such an assumption has already been introduced in a research of exploding wires of gold.(8)

Beyond the Point T, experimental curve exceeds considerably beyond the calculated curve. And Enthalpy required to get the same resistivity is smaller for the experimental curve than that for the theoretical curve.

An image converter camera is used for streak observation of the process of the development of the plasma. Fig-4 shows a typical streak photogram and illustration around the element of the model PPF. In Fig-4, the rapid growth of the emission finishes within 15 μs.

The resistance of the plasma varies from 100 to 410 m Ohm during τ and the averaged resistivity is 0.18 to 3.3 m Ohm-cm, assuming that the plasma is homogeneous in the quartz tube of d_o = 1 and length of 10 m/m.

It should be noted that the experimentally obtained value of the resistivity is smaller by almost two orders of magnitude than the classical resistivity.(9) The same order of magnitude of resistivity has been reported for dense non-ideal plasma of Cs(10).

(ii) SPECTROSCOPIC OBSERVATIONS FOR THE PLASMA DURING τ Spectroscopic observations of the sodium plasma in the model PPF have been made to estimate the order of physical state of the plasma.

The time integrated spectrogram obtained at the circuit condition of the second case shows that continuum spectra are observed over the wide range of the wave length between 2500 Å and 1 μ.

Typical spectra are given in Fig-5(a). Line spectra of Hg are superposed as reference lines. Current transients are coupled with each spectrum.

The time resolved spectrogram for three different lines with wave length of 4564. 4960 and 6090 Å shows that the sodium plasma emits the continuum spectrum during τ only when current abruptly decreases by an increase of the resistance of the sodium plasma.

Fig-5(b) shows temporal change of the intensity observed with one of three photomultipliers which is adjusted at 4563 Å. A corresponding current waveform is attached to Fig-5(b). Relative intensity of continuum spectra obtained by Fig-5(a) is given in Fig-6. Solid lines in Fig-6 give relative intensity of a black body radiation at the temperature of 3450 and 2000 °K. The experimental data plotted in Fig-6 agree closely with those of black body radiation. Good correlation is confirmed between the instantaneous value of the current at the beginning of the current limiting period and the estimated temperature. When the instantaneous value of the current is high, the estimated temperature becomes high due to high energy injection rate to the sodium.

The arc pressure can be roughly estimated to be the order of 10^4 atm, under the assumption that the plasma is ideal gas of the temperature 2000 $\sim$ 5000 °K and the particle density 1.7×10^{22} cm^{-3} of liquid sodium at boiling point. But reduced pressure $e^2 n_e/6\rho_D$ (ρ_D; Debye radius) obtained by real gas effect(11)(12) for 10 % ionized plasma is the same order of the pressure calculated above. Therefore, it seems that the arc pressure during τ is far lower than 10^4 atm.

(iii) SPECTROSCOPIC OBSERVATIONS DURING $\tau + T_f$ For the plasma during $\tau + T_f$, self-reversal NaD line and other broadend sodium lines are observed on to the continuum spectra.

An example of the time integrated spectrogram is given in Fig-7(a). Time resolved observations of the spectral lines around NaD including 5890 Å were made as shown in Fig-7(b). One of NaD lines, 5890 which is recognized during the period τ disappears beyond T_f. While, 5915 and 5875 Å lines are recognized for 1 ms. getting into T_f period.

From these spectroscopic studies, it is deduced that the plasma during τ is closely black body and the plasma during T_f is considered to be optically thin, since the self-reversal NaD line and other broadend lines are observed during T_f.

The electron density in the plasma during T_f has been estimated to be the order of 10^{18} cm^{-3} from Stark broadening(12) of the spectral line of NaD which is given in Fig-7(b).

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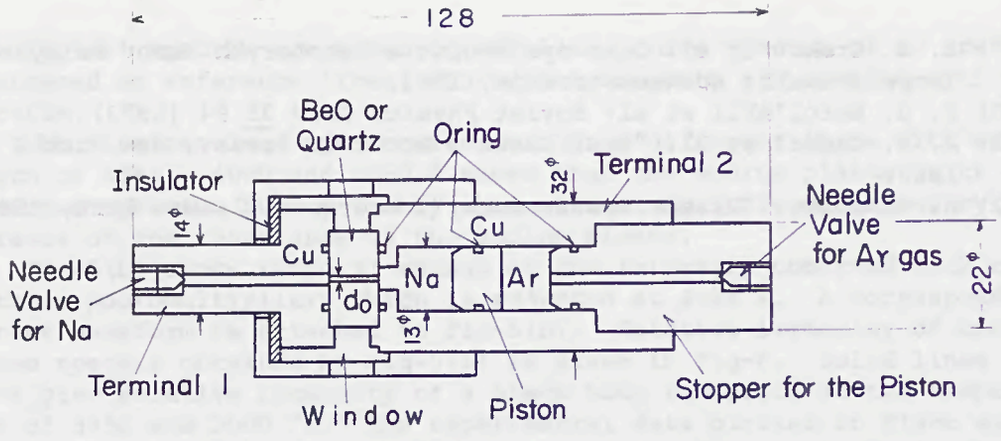
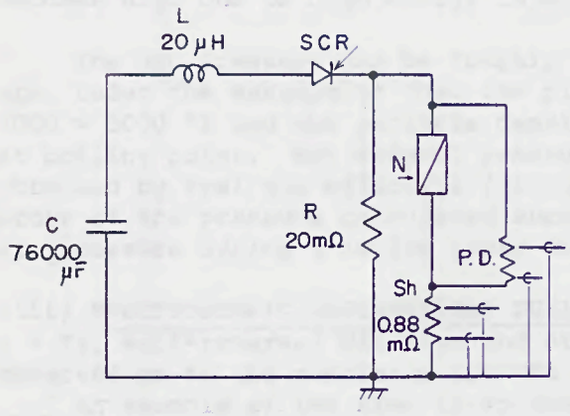
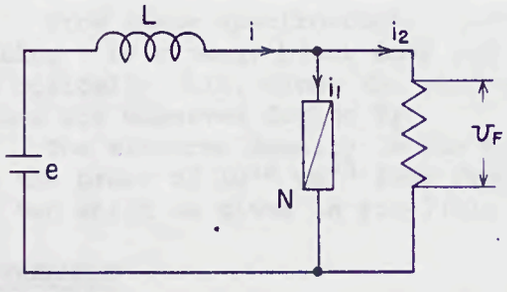


Fig.1 Cross sectional view of model PPF



(a)



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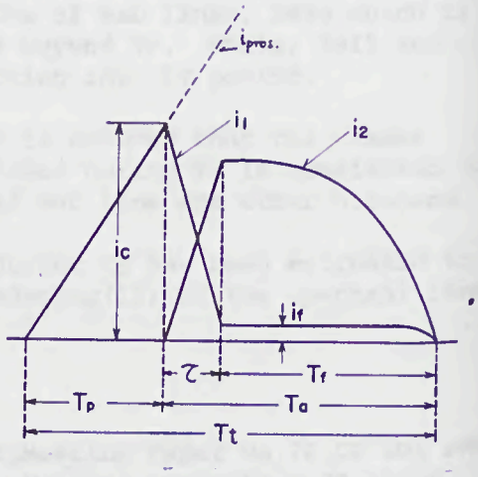


(c)

Fig.2 Circuit diagram and current waveform.
(a) Circuit diagram.
(b) Simplified skelton circuit of the test circuit.
(c) Schematic drawing of the waveform of i_1 and i_2.

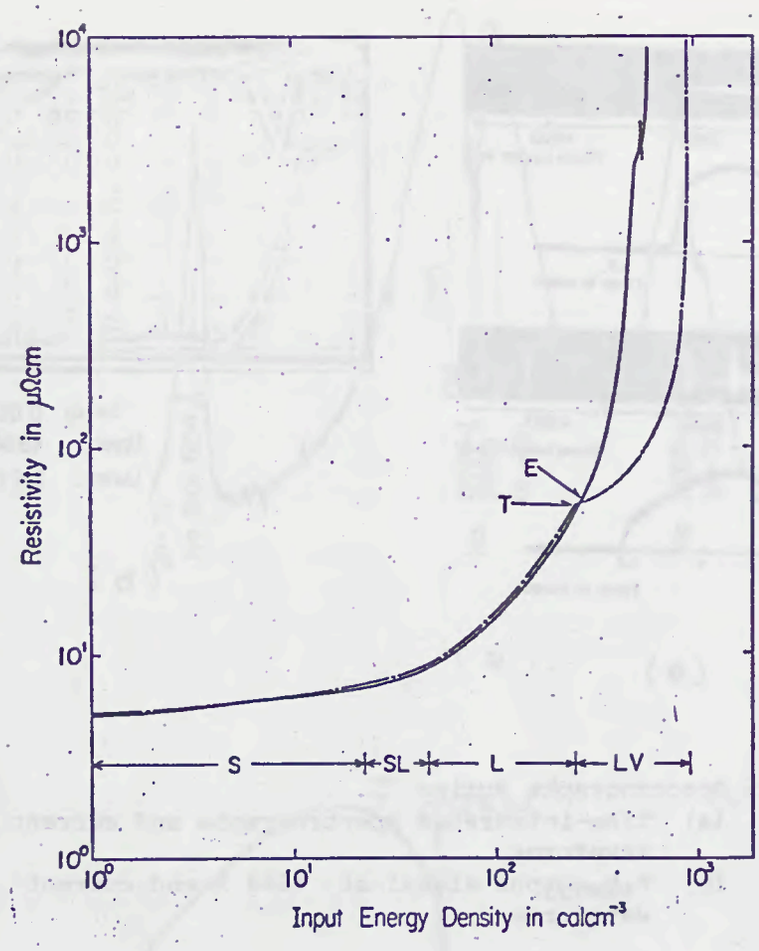


Fig.3 Resistivity of sodium in capillary versus input energy density.

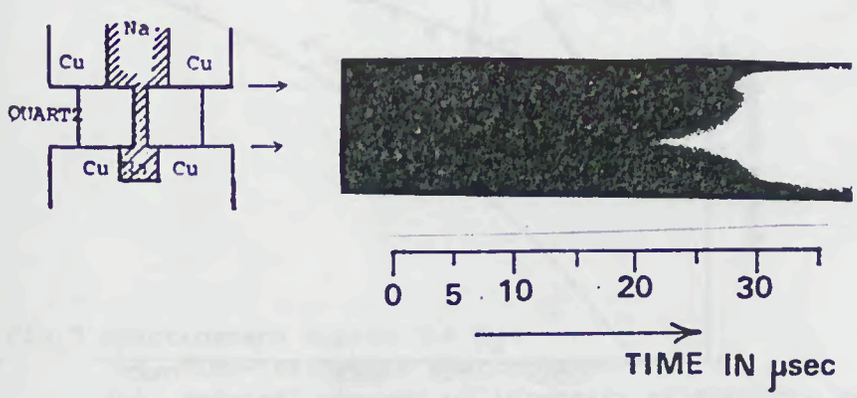
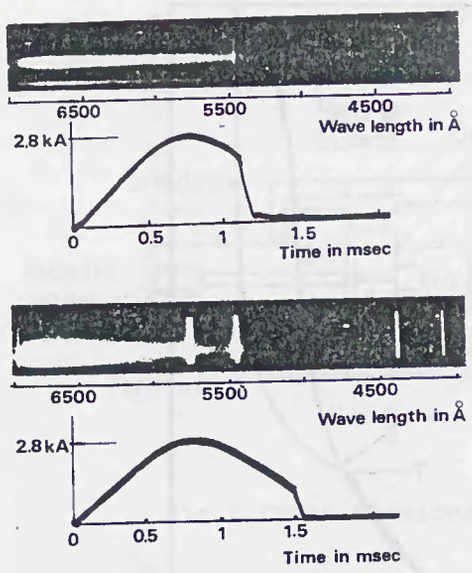
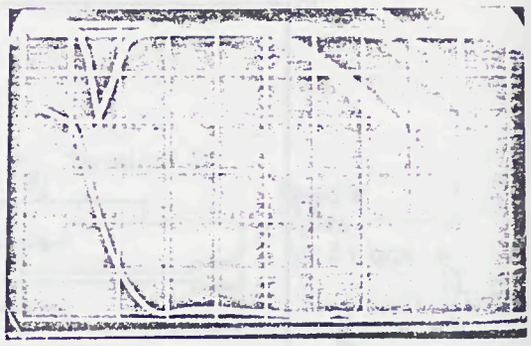


Fig.4 Streak photograph by image converter camera.



(a)



Sweep 0.05 msec/div
Upper ; 4564 Å
Lower ; 0.57 kA/div

(b)

Fig.5 Spectrographs during τ.
(a) Time-integrated spectrographs and current waveforms
(b) P.M.output signal at 4564 A and current waveforms

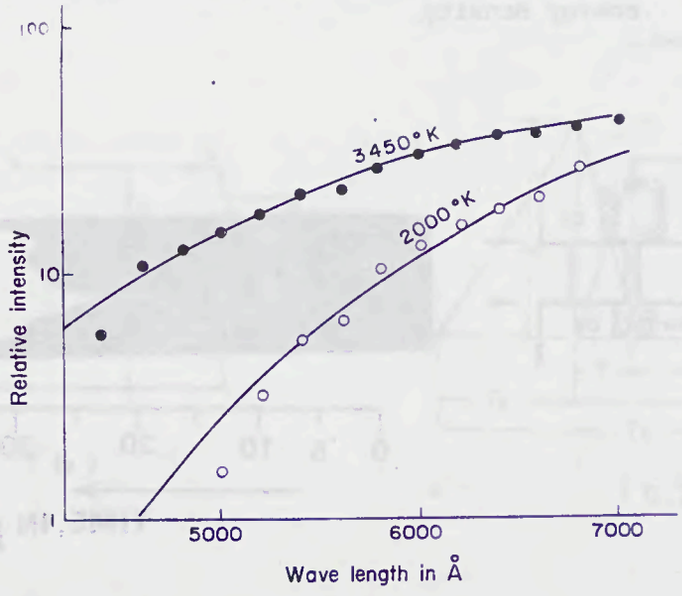
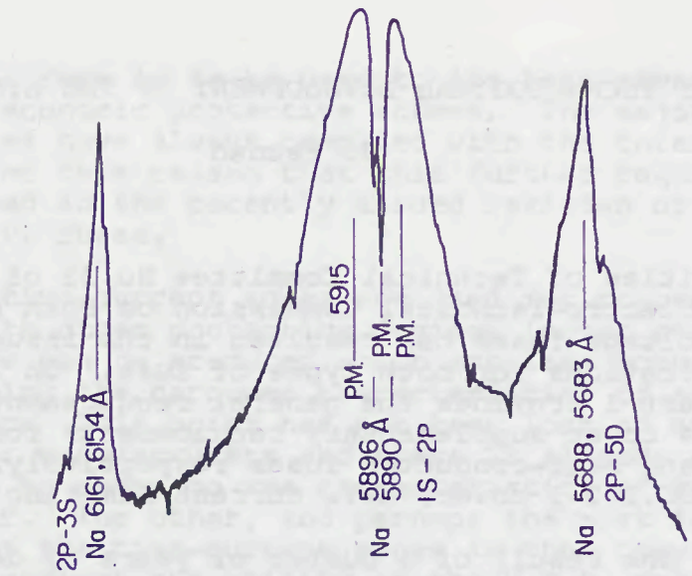
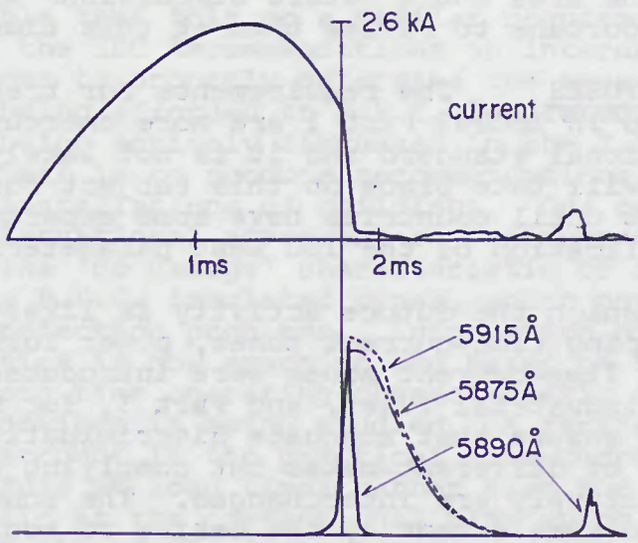


Fig.6 Relative intensity of continuum spectra. Solid curves show the relative intensities calculated for the black body.



(a)



(b)

Fig.7 Spectrograph during $\tau + T_f$.
(a) Time-integrated spectrograph
(b) Temporal changes of intensity of spectrum around Na D lines.