Investigation of Radiating Z-Pinches for ICF

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Abstract. The creation of an installation intended to investigate the problem of thermonuclear target ignition includes experiments on of X-ray pulse generation at compression of wire arrays, calculations of compression processes for these arrays and making a prototype of a 50 MA generator module. The investigations are being conducted at the Angara-5-1 facility. The current and density distributions during the process of implosion have been obtained and compared with the 1D and 2D calculations. The investigation results of making a prototype module of the Baikal facility are presented.

1. Introduction

Among the promising energy sources for CTF are high power radiating Z-pinches producing X-ray pulses of power sufficient for ignition of a thermonuclear target. At present, Z-pinches on the basis of multiwire arrays from materials with large Z are capable of producing the highest energy pulse of X- radiation. The creation of an installation which enables target ignition due to radiation arising at compression of arrays require investigations to be performed in the following directions:

-Study the processes of compression and generation of radiation in high current radiating Z-pinches.
-Development of radiating Z-pinch compression simulation.
-Creation of generators and circuits to supply electric pulse energy to a radiating Z-pinch with their parameters sufficient for ignition.

These investigations are carried out by the co-operation of the RRC the Kurchatov Institute, the SRC RF TRINITI, the SUE NIIFA and RFNC VNIITF. Physical investigations are carried out in the RRC the Kurchatov Institute and the SRC RF TRINITI. The works with a current of up to 5 MA and a pulse rise time of 100 ns are performed on the Angara-5-1 facility located in the SRC RF TRINITI. The basic efforts are focused on studying multiwire Z-pinches consisting of several tens – hundreds of tungsten wires 4-6 μm in diameter. When such wires compressed, a radiation pulse of a 6-12 ns duration and a power of up to 7 TW is generated. The radiation spectrum is of a quasi-thermal character with a temperature of 80 to 100 eV. The investigations of the wire array compression process have been carried out on the Angara -5-1 facility earlier [1] where the number of wires was from 2 to 20 and their diameter from 10 to 15 μm. Their results showed that when a megaampere current with a rise time of 80-100 ns flows through the wires, they do not displace to the axis as a whole, and their substance flows to the array axes for almost the full time of the current pulse. Up-to-date multiwire arrays produce shorter and more powerful X-ray pulses, particularly those consisting of nested arrays. To investigate such multiwire arrays we use frame images and temporal streak cameras in self-radiation in the X-and visible ranges and electrotechnical measurements. To study the mass distribution in the compression process a technique of probing an array to be compressed by the X-pinch radiation has been developed. To measure the current and magnetic field distributions inside the array under compression magnetic microprobes have been also made. These techniques permitted obtaining both new information that elucidated the physical understanding of the subjects in question and quantitative data to test the calculation codes.

2.Measurements of density distribution in the process of compression.

Among the methods to determine an absolute magnitude of the substance density is probing the plasma by radiation of a point X-ray source. The density of the plasma probed can be measured by the coefficient of absorption of the probing radiation. At the Angara-5-1 facility the plasma probing inside single and nested arrays was implemented by X-pinch radiation [2], the information on the attenuation degree of the X-radiation passed through the object under study was extracted by detection of this radiation on photofilms. The main objective was to receive information on a quantitative distribution of the subject mass. A procedure of the experiment on probing multiwire nested arrays is shown in Fig.1. and a temporal signal diagram in Fig.2. The adjustment was performed so that the films could detect the image of the region both inside and outside the inner cascade. In our experiments the films were placed 1.2 m from the X-pinch. The X-pinch looked like four cross molybdenum wires 20 μm in diameter which contacted in the middle of its length. The X-pinch was placed instead of one of the eight reverse current leads (at a distance of 45 mm from the liner axis). In one pulse the X-pinch radiates (in the X-range) more than 0.2 J to a 4π steradian angle [3]. The image was detected on four films fixed against each other. PIN diodes were used to measure the moment and duration of the X-pinch flash. The FWHM of the X-pinch radiation is ~1.5 ns in the energy region of quanta >2 keV. The size of the X-ray source on the basis of the X-pinch is less than 2 μm in the energy region of quanta >4 keV. The spatial resolution of the technique allowing for diffraction in terms of the object is not worse than 4 μm. To verify this resolution and to determine the source size test wires 5 μm in diameter with no current flown through them were set near the liner under study. Such a wire 5 μm in diameter is reliably detected. To provide the transition from the density of blackening of the photomaterial emulsion to that of the liner substance a step-like attenuator from tungsten was set in front of the photofilms. An image of a part of the nested array 60 ns prior to the maximum of the X-ray pulse is shown in Fig.3. At the bottom right there is a profile of the area density (integral taken over the probing beam) in the radial direction along a straight line a)

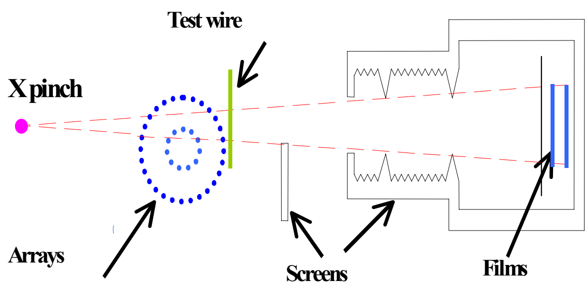

Fig.1. Density measurement by X-pinch radiography.

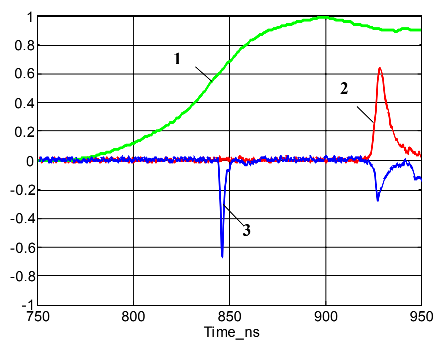

Fig.2. Oscillograms: 1-discharge current (1MA/div), 2 - SXR Z-pinch profile (a.u.) and 3 - X-pinch radiation profile (a.u.)

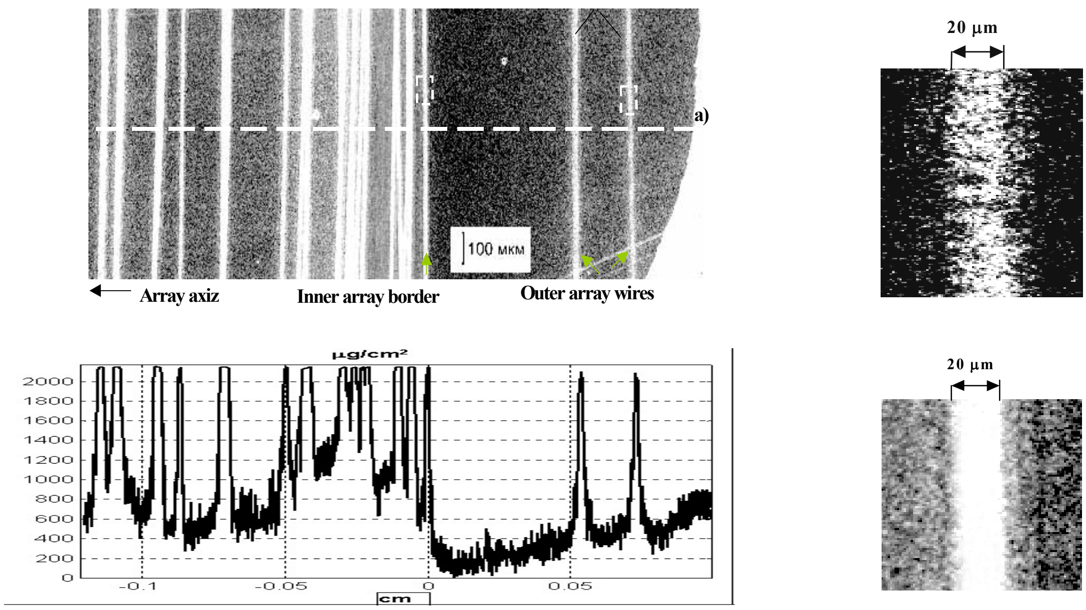

Fig. 3. Above: on the left - an image of a part of the outer and inner arrays, and on the right - a magnified fragment of the outer array wire. At the bottom: on the left - a plot of the integlral- over-the -probing- beam plasma density and on the right - a magnified fragment of the inner array wire.

The array radius is plotted on the abscissa. The coordinate 0 corresponds to the boundary of the inner cascade of the array. The array axis coordinate is -0.6 cm. An image of a part of the nested array 60 ns prior to the maximum of the X-ray pulse is shown in Fig.4. At the bottom right there is a profile of the area density (integral along the probing beam) in the radial direction according to a straight line a). As seen, only an insignificant fraction of the outer array plasma achieved the inner cascade This plasma is displaced towards the axis about 800 µm from the outer cascade wires. The inner cascade plasma is mainly displaced along the radius not farther than 150 µm. As to the inner cascade wires, the major part, i, e, ~80% of the substance is inside the dense core. The remaining 20% are distributed towards the array axis. As to the outer cascade wires, around 60% of the initial mass is in the core. In comparison with the substance of the inner array wires a major part of the substance of the outer array wires abandoned the core. Fig.3. (on the right there is a magnified core image) shows an inner core structure of the outer cascade wires. The core looks as if cut in the axial direction with a space of about 20 µm. The wires of both the inner and the outer cascades increased their visible diameter by the same value (from 6 µm to 20 µm, i.e. by about 3 times).

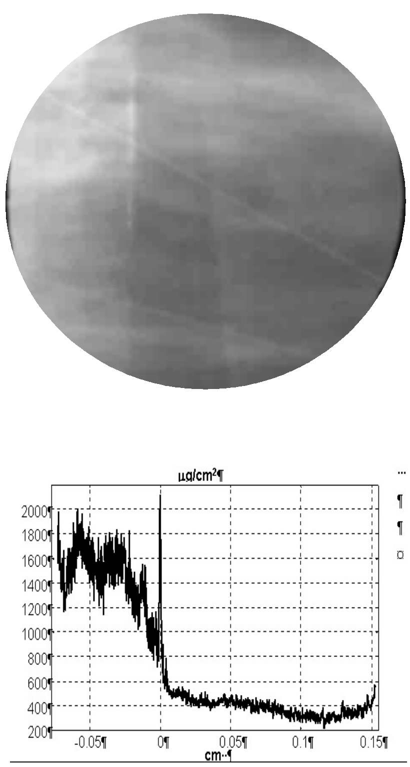

Fig. 4. The image of a part of internal array (above). Below density profile (integral along a beam of probing on a line a))

Fig. 4. shows an image of the nested arrays. The inner array (of 8 W wires 6 µm in diameter, its diameter is 12 mm and the outer array of 40 W wires 6 µm, its diameter is 20 mm) 35 ns prior to the X-ray maximum. The wire substance of the inner cascade, significantly, has transited to a plasma state and flows to the array axis. No

cores of the inner cascade wires are observed. The substance of these cores became diffuse. The wire cores of the inner cascade is nonuniform not only for different wires, but also for each wire of the array along its axis with a space around a millimeter. Such nonuniformly evaporated wire can be seen in Fig.4. It is evident that the major fraction (~70%) of the outer array substance is concentrated in the region about 0.5 mm along the radius.

The fact that the core widths of the inner and outer array wires coincide (Fig. 3.), though the current through the inner array is much greater than that through the outer one, proves that the process of forming the cores and the their velocity of expansion is independent on the magnitude of the current flowing through the wire a few nanoseconds later after the current start. It is supposed, that in our conditions, as it has been pointed out in [4], the current through the tungsten wire disappears for first 3-4 ns and further it keeps flowing through the plasma surrounding the wire. The wire substance being heated to ~2000° C expands at about a thermal velocity in the form of dust or droplets. The data on the density distribution confirm immobility of dense wire cores over the whole current pulse and formation of a layer ~0,5mm thick prior to the moment of arising the X-ray pulse.

2.Measurements of current distribution in the process of compression

A layout of the magnetic probes is demonstrated in Fig.5. The azimuthal probes were located inside the inner array, between the arrays and outside the outer array. they were put 2 mm deeper into the interelectrode gap. Each of the probes consisted of two opposite in direction loops 0.3 mm in diameter. An example of probe signals is given in Fig.6. The measurements made on the single arrays showed that the magnetic field inside the initial radius of the array (position 2 in Fig.5) is by 30-40% less than that measured by probe position 3, i.e. at the initial radius there occur a magnetic field jump. According to [5, 6] the jump is attributed to the wire plasma acceleration to a local Alvfen velocity inside boundary layer. In the process of such acceleration the ratio of the magnetic field outside and inside (beyond the boundary layer) the array is independent on the rate of plasma formation $H_{out}/H_{in}=(3)^{1/2}$, where H_{out} and H_{in} is the magnetic field outside and inside the array, i. e, beyond the boundary layer area. This ratio is justified by measurements taken on single arrays. As to double arrays, the ratio of the magnetic field magnitude immediately outside and inside the outer array radius depends on the radius and the number of wires of the inner array. For a small number of the inner array wires this ratio coincides with that for a single array, and with an increase in the wire number it approaches to unity. Fig.7 shows microprobe signals for a double array. Quantity $I=H*r$ is plotted, where r is the radius of the probe location and H is the magnetic field measured by the probe. This magnitude is close to that of the current flowing inside the probe radius.
The radii of the arrays and probes are displayed in Fig. 7. For the same outside array Fig. 8. shows a dependence of the currents I_2 and I_3 ratio upon the wire number in the inner array.

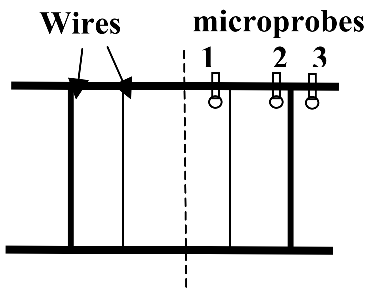

Fig. 5. Magnetic microprobes layout.

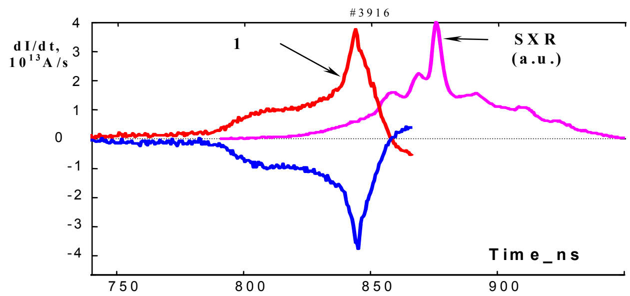

Fig.6. Signals of a magnetic field derivative from probe 1, taken on a 6 mm radius (two opposite loops).

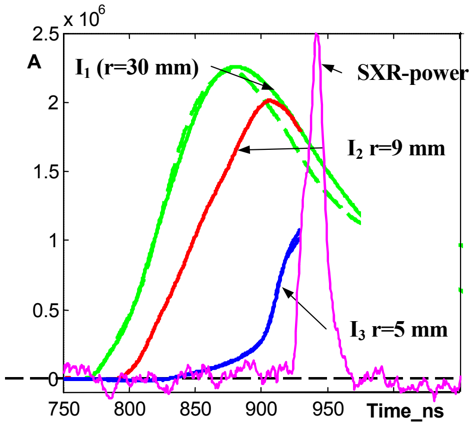

Fig. 7. Signals registered by probes 1.2, 3. Outer array: 40 W 6 microns wires on a diameter 2mmм, internal array: - 80 W-6 a micron wires on a diameter 6mm

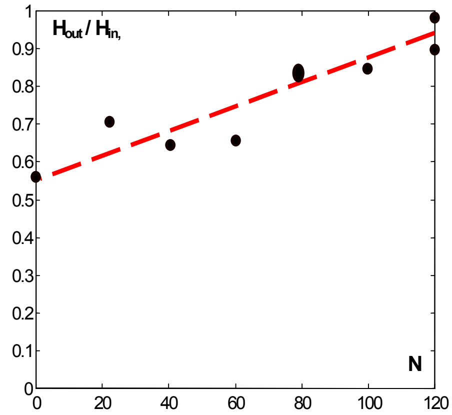

Fig.8. Dependence of the relation of a maximum of a current inside radius of 9 mm to a maximum of a complete current I_3/I_2 from wire number N in internal array

This obvious closing of the I_2 and I_3 magnitudes at increasing the number of wires in the inner array (in accordance with [5]) signifies both a decrease of the velocity to which the plasma in the boundary layer is accelerated near the initial radius of the outer array and a subsonic plasma flow between the arrays.

3. Simulation of a process of wire array compression.

A one-dimensional model [7] has explained the occurrence of the magnetic field jump at the initial array radius in the process of prolonged plasma production and allowed the moment of disappearance of dense wire cores to be calculated. Two-dimensional simulations of compression of single wire arrays were done in RFNC VNIITF [6]. Wire was calculated in an R-Z geometry (Fig.9.), and the entire array in an R-φ geometry. An example array calculation for the Angara-5-1 parameters is presented in Figs. 9. and 10. In Fig.10.the plasma flows from separate wires merge at a radius of around 0.6 cm due to gasdynamic instabilities. Along with this there form an area where the mass distribution from the angle becomes more uniform. In 40 ns about 5% of the total wire mass actually unuformly occupies a region inside the liner.

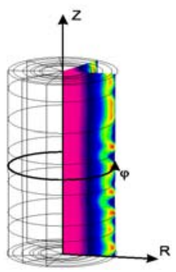

Fig. 9. Calculation scheme of a single wire of the array.

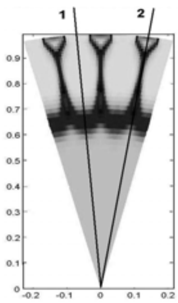

Fig.10. Mass distribution in the array.

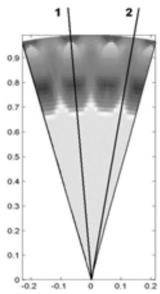

Fig.11. Magnetic field distribution in the array.

11-radius is between the wires and 2 - along the wire axis.
60 ns after current start.

As the numerical calculation shows, the main mechanism responsible for the magnetic field evolution is not diffusion, but a convective transfer of the field due to its freezing in. Since the velocity of substance motion in the regions between wires is much greater than under wires the magnetic field in these regions differs from that given by a theory of «snow plough». The magnetic field is not concentrated in the skin-layer, but penetrates to a large depth. The dynamics of magnetic field variation defines the substance velocity that is higher in the regions between the jets. However, at 90 ns the difference of magnitudes of the magnetic field between the wires and opposite to them is insignificant. This is in agreement with the experimental data obtained by making use of magnetic microprobes.

The time of radiation maximum is 145 ns. First, the X-ray in the period from 130 ns to 137 ns is associated with coming first jets of substance to the axis. Then, 140-145 ns later, there appear a near- axis area of greater density which radiates from outer layers. The fall of power (145-152 ns) is associated with starting scatter of substance from the axis. A slow power fall 152 ns later is a result of screening hot inner areas by cool dense areas. On account of reradiation outer dense layers are gradually heated.

4. Baikal project

In the SRC RF TRINITI concurrently with the investigations devoted to the physics of array compression in co-operation with the research institutes of the RF Atomic Agency, the Kurchatov Institute, RFNC VNIITF and SUE NIIEFA a project of the «Baikal»generator with a 50 MA current is under development. Its current by compressing wire arrays is to provide an X-ray pulse with its energy exceeding 10 MJ. Such a generator will permit investigations in thermonuclear target ignition to be performed. The basis of the project are four shock electric generators with an energy resource of 1 GJ each and an inductive storage TIN-900 with an energy resource of 900 MJ. This equipment was created in TRINITI for a high field tokamak several years ago.

Conversion of the energy stored up in the flywheels of the shock generators a current pulse is supposed to be generated in several successive sharpening stages. Due to extremely high parameters of the pulse output a module circuit of the generator is proposed. Fig.12. demonstrates corresponding stages of the process

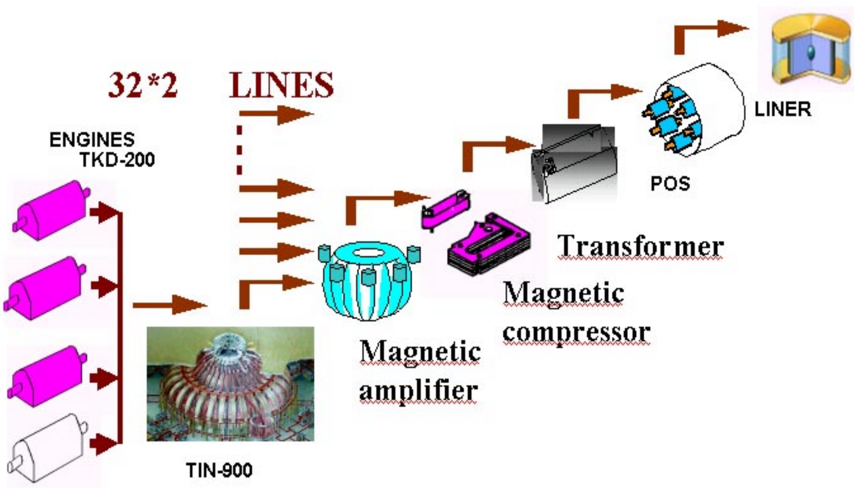

Fig.12. A schematic of the Baikal generator.

Such a complex circuit of energy conversion is attributed to the fact of giving up the employment of a large quantity of explosives. The equipment to sharpen the pulse prior to the time of the order of 100 μs has been developed and requires some technical updating. For sharpening stages from 100 μs to 150 ns further investigations are necessary. To develop the necessary equipment a MOL setup, i. e. a prototype of the Baikal generator module is under construction in TRINITI,. The module MOL is to generate a current pulse of 4.5 MW, 1.5 MJ and 150 ns. The MOL setup includes an inductive storage (IS) with an energy resource of 12 MJ, a capacitor bank (C) to increase the energy transferred from IS to the next sharpening cascade, a magnetic amplifier (MA) amplifying the IS current, a magnetic compressor sharpening the current pulse from 100 μs to 2 μs, a step-up transformer, a plasma open switch of current (POS) sharpening the pulse to 150 ns and an imitator of a variable load. The IS has been tested at a 30-fold current amplification, the magnetic amplifier constructed and the POS is under study. To make the current pulse duration shorter, from 100 μs to 2 μs, a magnetic compressor will be used. A capacitor bank will function as an energy supply for this compressor. A magnetic compressor works on the principle a flat magnetic- cumulative generator activated by electric current (Fig. 13.). Flat parallel plates from metal are accelerated under the action of the MA current and approaching to each other compress the magnetic flow produced in the working space. The flow is displaced by the plates to a load area where a current pulse with a short rise time is generated. We use the circuit given in Fig.13. There the plate is a strip that is folded in half and connected to a massive turn with a rectangular opening. The thickness of the turn located in vacuum is 25 cm, its length is 80 cm and the initial space between the strips is 20 cm.
The main difficulty in the conductor acceleration in planimetry is a nonuniform current distribution over the conductor width. As known, a current density at the conductor edges is higher than that in its middle part. This results in deformation of the conductor shape. The experiments of the first investigation stage were assumed to determine the size of this deformation. They were conducted with no initial magnetic field and in their most part with an aluminum strip 21 cm wide and 1.4 mm thick.

The strip shape was inspected with contact probes and rapid filming.The strip velocity was found to be 1 km/s at a final stage of the filming process. There are not any noticible deformations along its length. Deformation of the strip shape is displayed as an increase in the visible thickness of the film up to a magnitude of an order of 15mm. Its deformation is mainly reduced to a bend of the strip edges when moving downwards. To measure the degree of deformation, on the strip surface in its middle part a drawing in the form of a chess-board was painted. In its central part the strip is, in fact, undeformed, its edges are bent and the size of the bent region is ~ 20 mm for each edge, that makes up 20% of the total strip width.

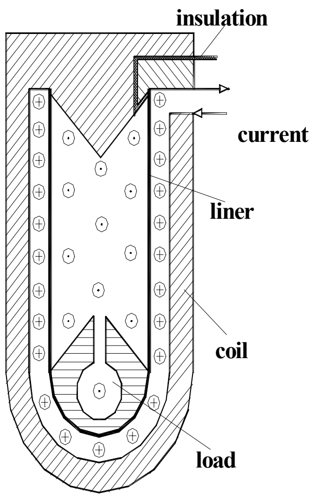

Fig. 13. The circuit of the magnetic amplifier

In the circuit used there is no necessity in an energy source capable of producing a magnetic field in the compressible volume. Magnetic field arises in the volume when an accelerating current is switched. The flow capture is executed with a switch that is one of the strip halves which cuts the slit. The slit position defines the magnitude of the flow captured. At a strip velocity of 1 km/s and capture of the utmost flow the stop of the strip halves at a distance of 10 mm was reached. Thus the experiments performed with the MC enable a success to be achieved.

5.References

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