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Camelot—A Novel Concept for a Multiterawatt Pulse Power Generator for Single Pulse, Burst, or Repetition Rate Operation

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Superpower pulse generators are fast establishing themselves internationally as candidates for employment in a wide variety of military applications including electronic warfare and jamming, high energy beam weapons, and nuclear weapons effects simulation. Unfortunately, existing multimegajoule pulse power generators such as AURORA do not satisfy many Department of Defense goals for field-adaptable weapon systems—for example, repetition (rep) rate operation, high reliability, long life, ease of operation, and low maintenance. The Camelot concept is a multiterawatt rep ratable pulse power source, adaptable to a wide range of output

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20. ABSTRACT (Cont'd)

parameters—both charged particles and photons. An analytical computer model has been developed to predict the power flowing through the device. A 5-year development program, culminating in a source region electromagnetic pulse simulator, is presented.

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1. NEED FOR CAMELOT

Present high-energy pulse power sources store primary energy in large capacitor banks and, with Marx voltage multiplying circuitry and Blumlein pulse forming techniques, deliver this energy to suitable designed loads in power pulses of tens of nanoseconds. The Harry Diamond Laboratories AURORA is the most representative high-energy operational example of current technology.

Unfortunately, these systems require very long development and procurement times and are very expensive to acquire and sustain in operation. Additionally, the large dimensions of such systems and the multitude of components used in their design cause extensive, difficult, and hazardous maintenance with concomitantly long system downtimes. These machines also require enormous fixed installations to house them and their specialized operation and maintenance staffs. Finally, existing technology cannot be adapted to provide more than a few shots per day, nor can it operate at requirements of pulse repetition (rep) rates of the order of kilohertz or higher. Only by technological innovation can progress be achieved.

The Camelot pulse power generator has been conceived as an improvement over conventional systems because

- Camelot acquisition and operation will cost significantly less than those of current systems.

- Camelot will adapt to single pulse, burst, and rep ratable pulse operation, whereas current systems have only single pulse operation.

- Camelot will be flexible enough to readily generate various values for voltage, current, pulse duration, rise time, and prepulse amplitude.

2. CONCEPTUAL DESIGN AND OPERATION

The generic Camelot system layout is shown in figure 1. The principle of operation is as follows.

Rotary flux compressor (compulsator) subsystem.—A rotary flux compressor (compulsator) is proposed as the preferred prime power source. This generator concept was originated and developed by the Center for Electromechanics at the University of Texas, Austin. Superior to conventional capacitor banks as a primary energy store, it is compact and rugged and can be adapted to operate in all modes—single pulse, burst, and rep rate. Its only disadvantages are its relatively low output voltage (≅75 kV) and its inability to generate significant energy pulses of less then ≅50 μs duration.[1,*]

Pulse transformer subsystem.—The compulsator is used as the input driver of a high-voltage (≅5 MV) output pulse transformer of the type developed by Rhowein of Sandia National Laboratories.[2,3] Plans for its development indicate that a pulse transformer with the capability of passing 200 kJ per pulse should be available for test in 1983.

Torus capacitor.—The transformer output pulse-charges a dielectric liquid-filled torus, whose inner conductor is supported by a set of

[1]*W. F. Weldon, W. L. Bird, M. D. Driga, K. M. Tolk, H. G. Rylander, and H. H. Woodson, Fundamental Limitations and Design Considerations for Compensated Pulsed Alternators, 2nd International Pulsed Power Conference, Lubbock, TX (June 1979).*

[2]*G. J. Rhowein, A Three Megavolt Transformer for PFL Pulse Charging, IEEE Trans. Nucl. Sci.,* **NS-26** *(June 1979).*

[3]*G. J. Rhowein, Design of Pulse Transformers for PFL Charging, 2nd International Pulsed Power Conference, Lubbock, TX (June 1979).*

[*]*Keith Tolk, A Study of the Engineering Limitations to Pulse Power Discharge Time for a Compensated Pulsed Alternator, Los Alamos Laboratories Final Report N68-8899H-1 (May 1979).*

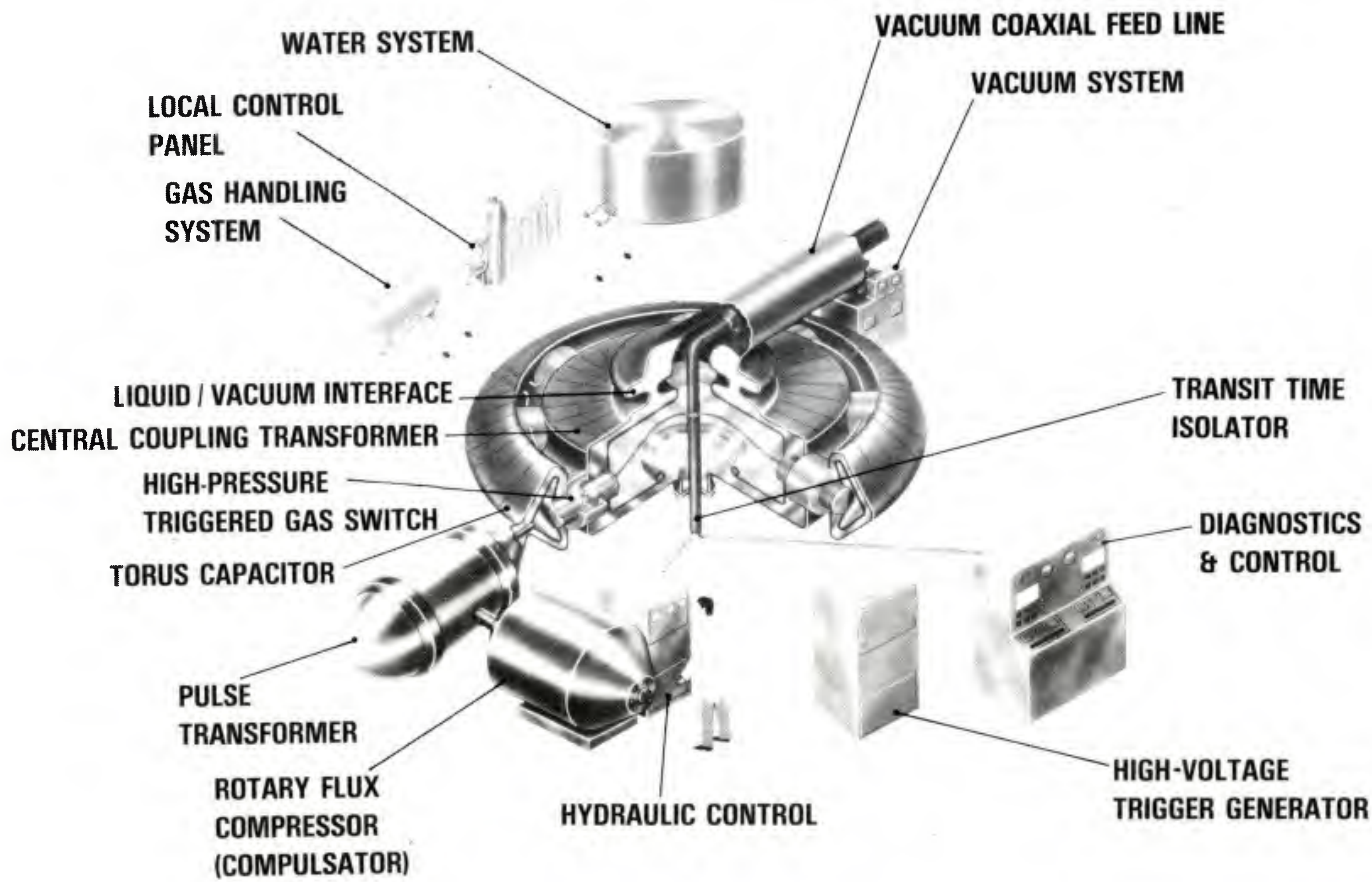

Figure 1. Generic Camelot system layout.

insulated bushings. The dielectric strength of such a large area liquid insulated system in the 50- to 500-μs regime is not as well known as the dielectric strength of either the dc voltage regime or the <10 μs regime. However, study in this time regime is not completely unknown.[4,5] Such research suggests that field gradients of at least 200 kV/cm should be achievable provided that precautions are observed for liquid handling and electrode surface preparation. Sufficient information also exists to indicate that the flashover strength of the bushing support structure on the liquid/gas interface is sufficiently high to ensure reasonably small dimensions of the torus.[6]

High-pressure triggered gas switch.—After the pulse charging of the torus, the electrostatic energy stored in the torus is switched out by the set of synchronously triggered high-pressure gas switches. In contrast to the long charge times, the torus discharges extremely rapidly (in a few tens of nanoseconds), the discharge time being determined as approximately the time that an electromagnetic wave travels around the minor diameter of the torus, assuming that there are a sufficient number of peripheral switch sites.[7] The high-pressure triggered gas switches are housed by the bushing support structures. Switches with the necessary operating characteristics (<10 ns jitter and >5 MV) are known to be feasible and could be readily derived from the devices reported earlier.[8,*] Also, this set of closing switches is the only high-energy switch requirement in the Camelot design.

This use of only gas switching is an important improvement over conventional technology, which depends on switching high energies through liquid. The recovery times of such liquid breakdown switches are much too long to permit rep rate operation. Since the only set of switches in the Camelot design uses gas, the system is compatible with rep ratable pulse operation.

Central coupling transformer.—The torus discharges its energy into the central pulse shaper (coupling transformer). This transformer may be filled with a different liquid than that used in the torus—preferably, water. This system design feature permits higher voltage traveling waves to be propagated toward the load because the component of the energy that is propagated in the lower channel reflects from the open-circuited inner boundary and superimposes itself on the forward propagating electromagnetic wave in the upper channel. These combined waves are then incident on the liquid/vacuum dielectric barrier interface before passing down the vacuum coaxial feed line (coax) to the chosen load.

Liquid/vacuum interface.—This liquid/vacuum interface is unique in pulse power system design.* A liquid interface is much less vulnerable than a solid interface to the effects of volume electrical breakdown since liquids, unlike solids, are self-healing. As used here, the liquid must be less dense than water, have a low vapor pressure, and have a high surface flashover strength to pulsed voltages. Many commercially available liquids appear satisfactory for this purpose (table 1). Experimental verification of these requirements is ongoing in the development of pulse power source technology at the Harry Diamond Laboratories. When successful, substituting a liquid/vacuum interface for the present solid structures will reduce costs appreciably.

[4]*W. D. Edwards, Some Results on the Electrical Breakdown of Liquids Using Pulse Techniques, Canadian J. Phys.,* **29** *(1961), 310-324.*

[5]*D. B. Fenneman and R. J. Gripshover, The Electrical Performance of Water Under Long Duration Stress, ICCC Conference Record of 14th Pulse Power Modulator Symposium (3-5 June 1980).*

[6]*P. I. McNeall and D. J. Skipper, The Impulse Flashover Strength of Solid Insulators in Compressed Gases, International Conference on Gas Discharges and the Electrical Supply Industry (May 1962).*

[7]*A. G. Stewart, High Power Pulse Compression Techniques, U.S. Patent 4003007 (11 January 1977).*

[8]*D. B. Cummings, A 3 MV Low Jitter Triggered Gas Switch, 2nd International Pulsed Power Conference, Lubbock, TX (June 1979).*

**A. G. Stewart and D. A. Ameen, Ion Physics Co., Boston, MA, Report 67736 (August 1964).*

**Patent pending.*

TABLE 1. CANDIDATE LIQUIDS FOR LIQUID/VACUUM INTERFACE

Liquid	Density	Voltage pressure at 25 C (torr)
Amoil S (amyl sebacate)	0.925	10^{-6}
Apiezon A	0.87	5×10^{-6}
Apiezon B	0.92	5×10^{-7}
Atensol A	0.8853	5×10^{-6}
Butyl sebacate	0.933	2×10^{-5}
Myvane 20	0.85	10^{-6}
Narcoil 20 (sebacate)	0.91	10^{-8}
Narcoil 30 (sebacate)	0.98	2×10^{-7}
Octoil (phthalate)	0.98	2×10^{-7}
Octoil S	0.91	10^{-8}
Convalex 10	1.2	10^{-7}
Silicone 705	1.09	2.4×10^{-6}
Santovac 5	1.195	10^{-9}
Fomblin YVAC 18/8	1.89	2×10^{-8}

Vacuum coaxial feed line.—After passing through the liquid/vacuum interface, the electromagnetic wave is propagated to the load down the vacuum coax. If the radial fields at the surface of the inner conductor are kept below 250 kV/cm, no problems should be encountered with field emission. However, if radial fields above 250 kV/cm are produced, it will be necessary to choose a coax geometry and load that will ensure magnetic cutoff in the coax.

3. ALTERNATIVE CONFIGURATIONS

Alternative configurations for Camelot are shown in figure 2.

The pulse shape can be modified through alterations to the geometry of the *central coupling transformer*, the geometry of the torus, or both.

Less obviously, pulse shapes can be varied also by switching out the torus from only a few of the available *switch sites*. In this mode, the torus discharge time would be dominated by the circumferential discharging wave component, rather than the radial wave component. This would represent a very long output pulse mode of operation (microseconds).

With *energy diverter switches*, the trailing edge of these pulses could be crowbarred out, thus shortening the pulse duration and removing unwanted reflections. Typically, this technique could allow predictable pulse width variations with 10-ns resolution.

The pulse shape and its duration also may be modified by *plasma erosion switches*.[9,10] With the plasma erosion switches, it should be possible to sharpen the leading edge of the pulse that passes down the output coax. In that way, for example, a pulse with a nominal rise time of 75 ns could be reduced to having a rise time of 25 ns.

Other important hardware options can be used to provide significantly different pulse outputs. For example, if the object were to produce focussed *electron or ion beams*, then the coax would be tapered along its length to a few centimeters in diameter at the output.

If the voltage pulse duration is short compared with the electrical length of the coax, then the coax can be configured to transform the pulse, leading to higher or lower voltages out of the coax than injected into it. With this option, it should be possible to double or triple the voltage output. (In fig. 2, it is identified as the *increasing Z high-voltage modification*.)

For high-energy and relatively long-pulse (≅100 ns) operation, *water* can be substituted for the transformer liquid in the torus, given the following assumptions and precautions.

[9] *C. W. Mendel, Jr., and S. A. Goldstein, A Fast-Opening Switch for Use in REB Diode Experiments, J. Appl. Phys.,* **48** *(March 1977).*

[10] *R. Stringfield, R. Schneider, R. Genuario, I. Roth, K. Childers, C. Stallings, and D. Dakin, Plasma Erosion Switches with Imploding Plasma Load on the Pithon Generator, 21st Annual Meeting, Division of Plasma Physics, American Physical Society (November 1979).*

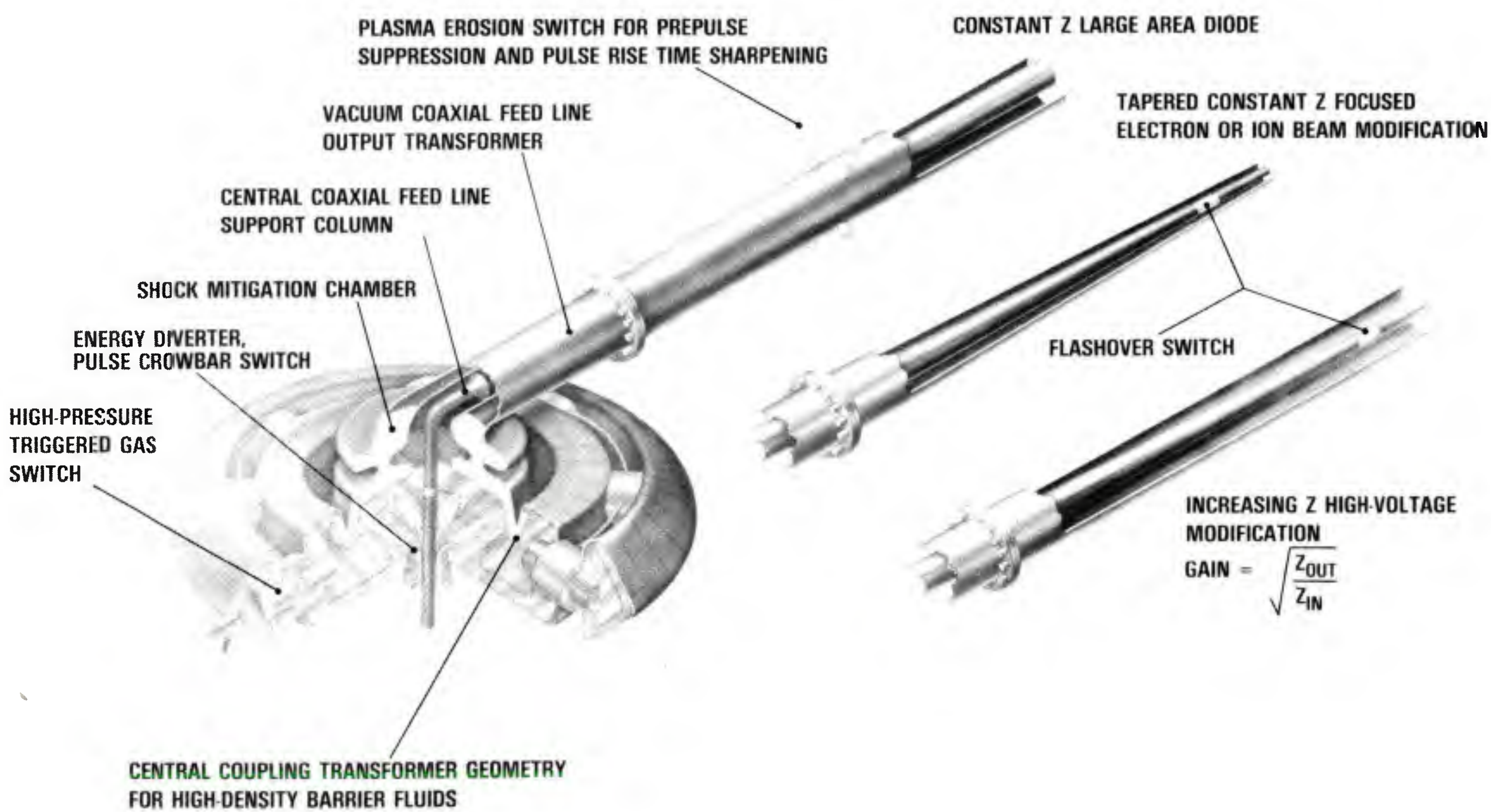

Figure 2. Options for Camelot componentry.

a. The torus can be charged in under 100 μs. This assumption is reasonable, given the advancing state of the art of rotary flux compressor technology.

b. The water is chilled to a few degrees celsius, demineralized, de-ionized, and deaerated; particulate matter over 1 μm is removed; and in some cases the water can be pressurized to 30 atm.

c. The macroscopic fields are properly contoured, the stainless steel electrodes are properly dressed by glass bead blasting, small surface roughness is removed by low-energy conditioning, and the system operates as a closed system. That is, no breakdown products from switch processes can be allowed access to the high-field, energy-storage region.

One additional feature makes the Camelot design singularly suitable as a pulse power source. The slow rate of pulse charging the torus and the relatively high capacitance of the central coupling transformer limit the system prepulse to very low values. Since prepulse cathode fields as low as 20 kV/cm can adversely affect diode performance, this low prepulse is an important design feature. Moreover, any pass-through prepulse can be dealt with effectively by judicious use of either a plasma erosion switch or a cathode flashover switch (fig. 2).

4. APPLICATIONS OF 1/4-MJ PROTOTYPE

The Camelot design is sufficiently compact for ready modularization. In one option (fig. 3a), four high-energy (5-MJ), high-power (25-TW) sources are arrayed around a common target area. These sources are assumed to be operating in the focussed ion beam mode. The power on target for this option should exceed 100 TW, assuming proper transport, bunching, and focussing of the ion beam. A second option (fig. 3b) has a low-energy (100-kJ), high-voltage (>10 MV), fast-pulse (≅25 ns FWHM) output in a modular array.

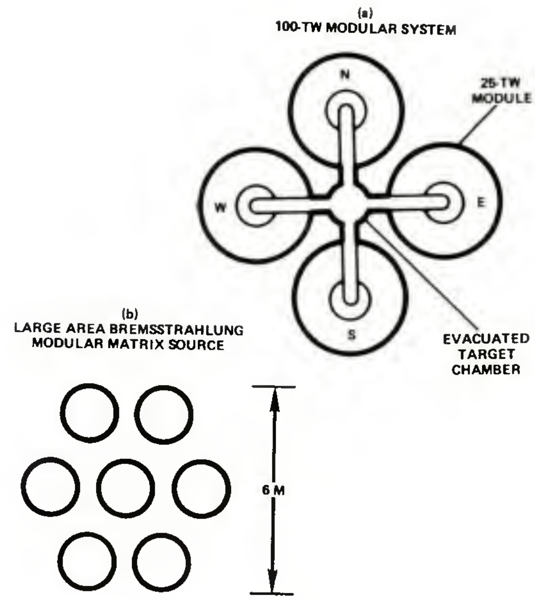

Figure 3. Camelot options for modularization.

In the Camelot system shown in figure 4, it is assumed that the torus energy store is filled with transformer liquid. For the dimensions shown in figure 4, but with a circular cross section rather than the triangular cross section shown (a more likely engineering design), ≈100 kJ could be stored for peak charge voltages of 5 MV and peak electric fields of 235 kV/cm. Given the present state of the art of flux compressors, the $t_{effective}$* would be ≈500 μs. Insulation breakdown is unlikely under these conditions.[4,5]

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[4]*W. D. Edwards, Some Results on the Electrical Breakdown of Liquids Using Pulse Techniques, Canadian J. Phys.,* **29** *(1961), 310-324.*

[5]*D. B. Fenneman and R. J. Gripshover, The Electrical Performance of Water Under Long Duration Stress, ICCC Conference Record of 14th Pulse Power Modulator Symposium (3-5 June 1980).*

**$t_{effective}$ is related to the dwell time at high fields and is defined as that time over which the pulse exceeds the 63-percent value of the peak field reached before breakdown, even if breakdown occurs after the peak of the pulse.*

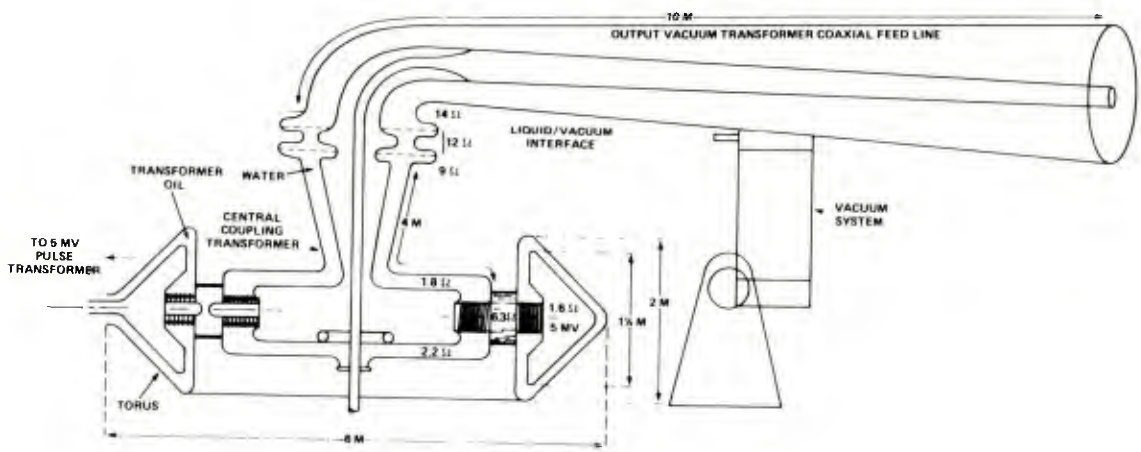
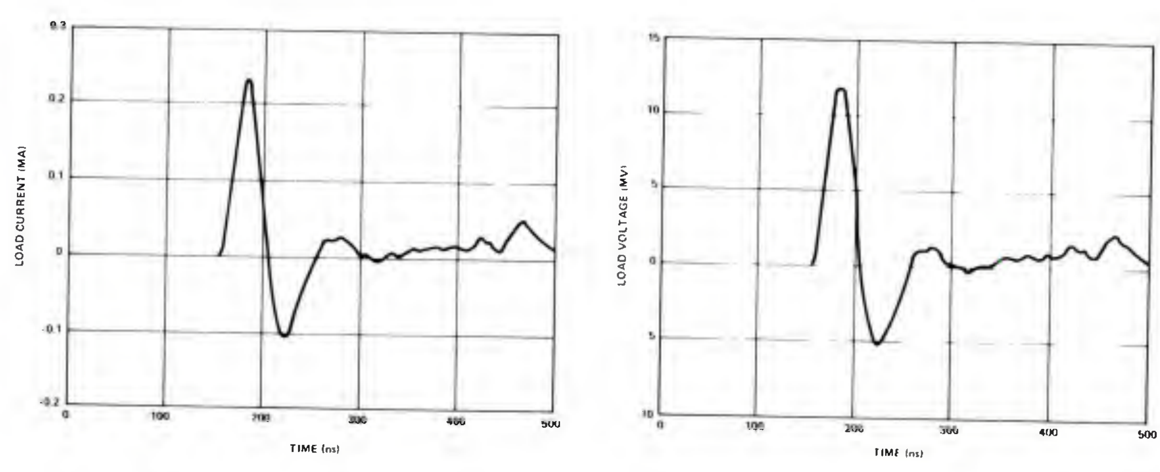


Figure 4. Proposed 1/4-MJ prototype of Camelot.

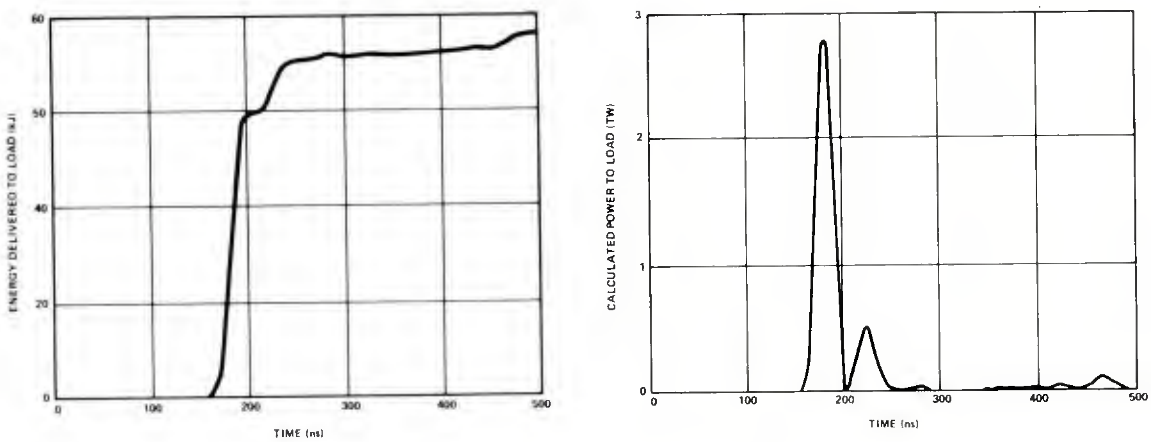
Also seen from figure 4, starting with the 1.6-ohm discharge impedance of the torus, an electromagnetic wave progresses through the 1.8- to 9-ohm impedance transformation of one central coupling transformer, through the 12-ohm liquid/vacuum interface, and down the 10-m-long vacuum output transformer to a 50-ohm load at the output. An electrical equivalent circuit model based on this design has been derived, and a computer analysis program based on this model has been developed. The code has been used to predict voltage, current, energy, and power pulses (fig. 5) for operation into a matched load. For this case, the energy delivered to the load is 70 kJ—that is, a transfer efficiency of 70 percent.



(a) LOAD CURRENT

(b) LOAD VOLTAGE

Figure 5. Predicted output of Camelot.



(c) ENERGY DELIVERED TO LOAD

(d) CALCULATED POWER TO LOAD

Figure 5. Predicted output of Camelot (Cont'd).

Although this is being classified as a 1/4-MJ prototype, this system is believed to have already the appropriate output characteristics to make it a viable power source for a number of known applications. For example, a source region electromagnetic pulse simulator is required to provide gamma dose rates of $\cong 10^{10}$ R/s over areas of a few hundred square meters. The required photon spectrum distribution and photon intensities are achievable by using a 12-MV electron beam impacting a high-Z bremsstrahlung target converter (fig. 6, 7). If an array of sources (fig. 3b) is used, the area requirement can be satisfied. Each source would be represented by a prototype module.

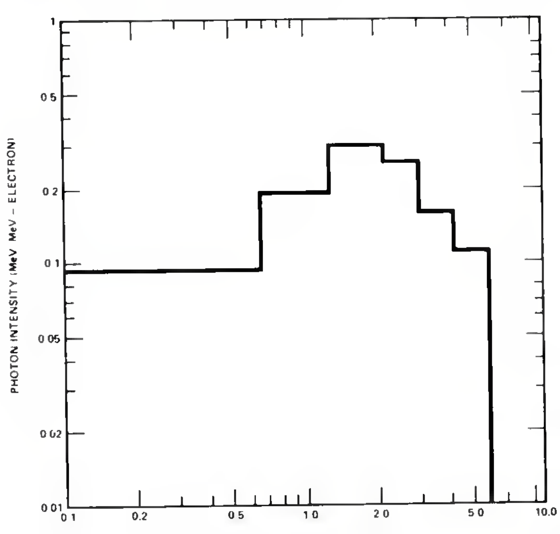


Figure 6. Typical bomb photon spectrum.

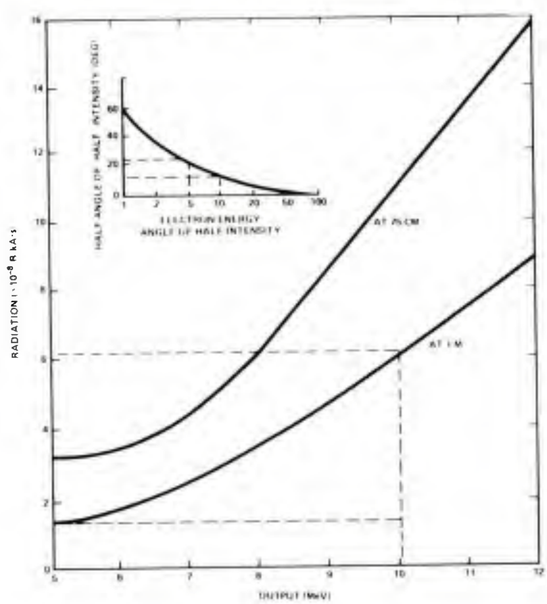


Figure 7. X-ray output.

5. PROPOSED DEVELOPMENT OF CAMELOT PROTOTYPE

The 5-year research and development program outlined in figure 8 identifies the major technological milestones for a prototype high-energy Camelot module. The goal is to produce a power source with a multiterawatt rep ratable pulse capability suitable for Army field applications.

6. CONCLUSIONS

Camelot is simple, compact, and rugged as a pulse power system concept. These characteristics make it attractive for weapon applications. An early successful demonstration of a 1/4-MJ prototype would be a significant step toward the development of the concept. The technical requirements for such a prototype are believed to be within the present state of the art.

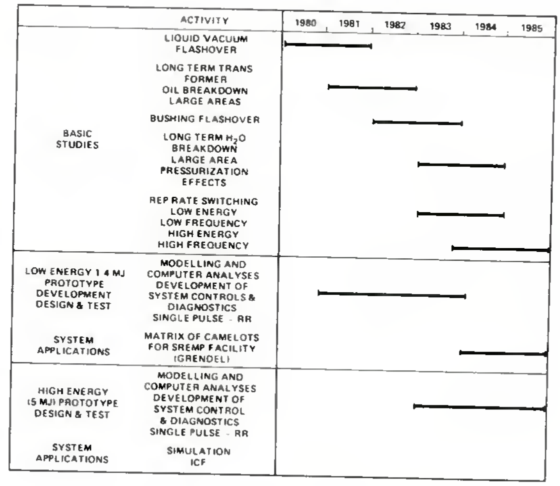


Figure 8. Camelot 5-year development program.

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