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L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

CANADIAN ACCELERATOR BREEDER SYSTEM DEVELOPMENT

Développement de l'accélérateur surgénérateur canadien

S.O. SCHRIBER

Presented at Symposium on Accelerator Breeder Technology held by the Electric Power Research Institute,
Palo Alto, California, 1982 June 09-10

Chalk River Nuclear Laboratories Laboratoires nucléaires de Chalk River

Chalk River, Ontario

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par

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RESUME

On prévoit une pénurie de matières fissiles à prix modéré au début du vingt-et-unième siècle. La transformation de matières fertiles en matières fissiles par des méthodes électronucléaires est une option qui peut ménager les réserves mondiales de matières fissiles en fournissant le combustible des centrales nucléaires. Ce rapport présente le bien-fondé des surgénérateurs électronucléaires et il décrit le programme canadien de développement d'un accélérateur surgénérateur pouvant produire 1 Mg de matières fissiles par an.

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ABSTRACT

A shortage of fissile material at a reasonable price is expected to occur in the early part of the twenty-first century. Converting fertile material to fissile material by electronuclear methods is an option that can extend the world's resources of fissionable material, supplying fuel for nuclear power stations. This paper presents the rationale for electronuclear breeders and describes the Canadian development program for an accelerator breeder facility that could produce 1 Mg of fissile material per year.

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I INTRODUCTION

Anticipated world shortages of fissile material for expanding networks of nuclear power stations have encouraged many countries to invest research and development resources in fast-breeder reactors and stand-alone fusion. An option that would make efficient use of the world's heavy element reserves and fill a gap in the fissile fuel demand is the electronuclear breeder, which converts ample reserves of fertile material to fissile material. Fissile material converted in an electronuclear breeder would be reprocessed and used in fission nuclear reactors that produce electricity for the world's consumption.

This paper presents a rationale for development of an accelerator breeder and gives details of an organized and logical development program that culminates in a Canadian facility. Current work and future plans are presented along with arguments that determine operating parameters, production rates, costs in 1981 Canadian dollars and development times. Accelerators discussed in this paper are operated 100% duty cycle, i.e., continuous wave (cw).

II NUCLEAR POWER AND THE FUTURE

Generation of electricity in the future will involve a higher percentage production from nuclear power stations than at the present. As more nuclear power stations are put into service, the strain on available uranium resources in the world will increase. Eventually uranium resources at reasonable prices will become scarce and improved nuclear cycles or systems will be required to offset this shortage. Means to produce fissile fuel for new and operating stations may have to be employed to overcome temporary and long-term fuel shortages. Research and development into the scientific and engineering aspects of producing fissile fuel from fertile material could be undertaken now, so that ample time would be available to bring this new concept to fruition and avoid serious power shortages in the future - development times of 20 to 30 years are usually required for complex systems.

Figure 1 gives a schematic picture of the evolution of nuclear power stations in the world and the related consumption of the world's fissile material supply. The figure is not to scale in either of the coordinates and only illustrates the order of events that could occur and the consequences implied for the world's fissile resources. Most nuclear power stations generating electricity today are based on a once-through fuel cycle or "burner" configuration that makes inefficient use of our heavy element resources. (However, this generation is economical in many areas of the world in terms of costs and resources when compared to other methods generating electricity.) The once-through cycle burns approximately 1% of the heavy element in the fuel, mostly ^{235}U (isotopic abundance in natural uranium of $\sim$ 0.7%). This ^{235}U, the only naturally occurring fissile material, will be depleted in time, with shortages expected in the early part of the twenty-first century if there is no conversion to more uranium conserving cycles. While fuel is being burned in nuclear power stations a small percentage of the fertile ^{238}U is being converted to fissile ^{239}Pu. ^{239}Pu resources stored in spent fuel will increase as ^{235}U resources are being consumed and spent fuel bundles are sent to storage - approximately 0.3% to 0.6% of the heavy element in spent fuel bundles is ^{239}Pu. It is estimated that about 100 Mg of ^{239}Pu will be stored in spent fuel bundles in Canada by the end of this century.

Breeder reactors will be employed in the future, during the period that natural uranium resources are depleting, to supply an electricity demand before stand-alone fusion is a viable power generator. Breeders include reactors operating on advanced thorium cycles (with breeding ratios near unity) and fast-breeder reactors. Doubling times for producing fissile fuel from fast-breeder reactors are relatively long, greater than 20 years. Introduction of fast-breeder reactor power stations into a system of many operating "burner" reactors will initially deplete fissile resources without producing inventory for new stations.

During the period that fast-breeder reactors are being commissioned, fissile supplies could be obtained by mining ^{235}U and by recovering ^{239}Pu from spent fuel, resources that are both being depleted. There are options for producing the topping enrichment and initial inventory requirements for operating and new stations. Fissile fuel could be obtained by converting fertile material to fissile material in suitable blanket configurations. Two electronuclear methods that are attractive for this conversion are fusion breeders and accelerator breeders. Technologically the accelerator breeder is closer to industrial practicability and would be the option available earliest. Eventually fusion-fission hybrids will operate with the fusion reactor supplying fuel for fissile reactors and producing power for the electrical network at the same time. Before such a hybrid is introduced there may be a window that the accelerator breeder could meet as shown in Figure 1. It is this need and this window that this paper addresses.

The discussion that follows is in the context of the Canadian nuclear power situation - the magnitude of the expected Canadian electrical demand and the employment of the unique CANDU (CANada Deuterium Uranium)* reactor system. Although Canada has sizeable resources of uranium and thorium, the price and availability of this resource will be tied to the world scene. When the world supply of fissile material becomes scarce, the accelerator breeder could represent a possible option for ensuring security of fuel supplies in an expanding system. The window could be affected or eliminated by many developments including further discoveries of uranium, more spent fuel from which to extract ^{239}Pu and stand-alone fusion being introduced earlier. Accelerator research and development work required to engineer an accelerator breeder keeps one abreast of technologies useful for fusion breeders or fusion systems - high power rf, high current beams, large magnets, materials damage, breeding blankets, shielding, neutronics, etc. Technology exchanges on related studies or components are possible benefits for the future.

Approximately 10% of the electric power generated in Canada is from 5 GW_e of installed nuclear capacity. Committed nuclear stations will increase the nuclear component to 10 GW_e in 1985 and to 15 GW_e in 1990. Projections for Canada in the year 2000 forecast an installed nuclear power capacity of about 25 GW_e that is increasing at the rate of 1 GW_e per year. If new stations after the year 2000 are based on CANDU reactors operating on advanced thorium cycles with a conversion ratio of $\sim$ 0.9, the fissile fuel requirement in 2025 for the 25 GW_e of advanced CANDU stations will be $\sim$ 10 Mg per year. Approximately 5 Mg will be required as initial inventory for the 1 GW_e being commissioned including material in out-of-reactor parts of the cycle and $\sim$ 5 Mg will be required as topping enrichment for the 25 GW_e of installed advanced thorium-cycle reactors. By the year 2025 shortages of reasonably priced uranium have been forecast[1] and the electronuclear breeder represents an option to supply a portion of the 10 Mg per year requirement. This requirement plus studies

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*CANDU is a registered trademark of AECL.

of parameters and costs for fuel breeders determines the size of individual fissile material production facilities - at least 1 to 2 Mg per year. To put this in context, the 10 Mg/a represents approximately 25% of the ^{235}U that is separable at 0.2% tails from the present Canadian 7000 Mg/a production of natural uranium.

The need for reprocessing and refabrication of fuel from the electronuclear breeder, suggests that the breeder should be sited at a nuclear park that has reprocessing facilities associated with advanced thorium-cycle CANDU reactors. Fissile fuel from the breeder would not have to be shipped off the nuclear park, reducing risks and costs associated with shipping radioactive material. A sharing of waste handling, turbo-generators, waste heat and other support facilities would be possible.

Recent assessments[2,3] of a fusion breeder (FB) and an accelerator breeder (AB) indicated that both could produce fissile material at a cost in 1981 Canadian dollars that was three to four times the assumed $48 per fissile gram cost of ^{235}U. Fissile fuel costing included the revenues received from the sale of surplus electrical power generated by the breeder. Capital estimates for both methods were roughly $1500 M per Mg/a fissile production rate. The fuel production rate of a FB was 2-3 Mg/a compared to an AB at 1 Mg/a. The FB produced about 1 GW_e of electricity whereas the AB produced 0.1 GW_e; power that would have to be fed to the electrical grid. Availability for a fuel breeder does not have to be as good as that for nuclear power stations whose primary function is generating electricity. Although the breeder generates electricity as a secondary function, its main purpose (producing fuel for power stations) is one stage removed from the generating process.

Advantages for an AB relative to a FB are that scientific feasibility has been proven and engineering problems appear to be much easier. Technology associated with the blanket and target may be as complex as that for a FB fertile-fissile blanket. No tritium breeding blanket is required, however. The reference design for an AB is smaller and can be reached by well-defined steps in an organized and logically staged development program. Each stage ends with a unique research and development facility and presents an opportunity for program reassessment in the light of current developments at the time. Similar opportunities exist for the fusion program that is also following a staged development program. For these reasons and because of the accelerator technology base at Chalk River Nuclear Laboratories (CRNL), we will pursue the first stage of an AB program while maintaining an active watch on developments in the world related to a FB.

III STAGED ACCELERATOR BREEDER DEVELOPMENT

An AB producing 1 Mg/a as a reference size has a 500 m linear accelerator (linac) that delivers 300 mA of 1000 MeV protons to a suitable target/blanket. Higher production rates could be achieved by raising the output proton beam energy, with an associated increase in the length of the accelerator. For example, a 2000 MeV linac producing twice as much fissile fuel would be 1 km in length. The estimated $1500 M cost for a 1000 MeV AB would represent a modest 2 m$/(kW·h) increase to the 26 m$/(kW·h) charged today in the province of Ontario - an 8% increase in the price of electricity.

The program for development of an AB in Canada involves four stages[4,5] shown in Figure 2. Each stage represents a reasonable step in technological development, builds on expertise developed in earlier stages and makes a reasonable investment in resources. Between each stage the program can be reassessed based on technological advances made in other fields, uranium prices and exploration potentials, nuclear power demand, and revised estimates of fissile fuel production. The first stage, for which approval is expected in 1983, will investigate the area of launching suitable beams for an AB. The second stage, to begin mid 1990's, will investigate operation of an intermediate energy linac with lower average current and provide a neutron source for materials test of breeder target/blanket components and a source of thermal neutrons for research. The third stage, beginning mid 2000's, is a pilot plant that will investigate aspects of target/blankets so that the final stage, starting mid 2010's, can be built based on a well-developed technology.

First Stage

The first stage of the program is a 300 mA, 10 MeV proton linac, ZEBRA (Zero Energy BReeder Accelerator), that will test all aspects of launching the full current beam for an AB. The energy is high enough, without being overly expensive, to study beam transport, high beam loading, multiple tank operation, higher order mode excitation, frequency multiplying between different structures, high power rf control and transmission, accelerator control, support systems, remote handling, accelerator turn-on, beam diagnostics, engineering techniques, emittance growth, shielding and reliability. Beam testing will be important for the design of following stages and for checking computer codes used to predict beam dynamics. Performance of higher energy portions of an AB will depend on how well the bunched beam was formed and accelerated in the first part of the accelerator.

The 75 keV ZEBRA proton injector has complete current variability from zero to the full 375 mA needed for injection into a 4 m long radiofrequency quadrupole (RFQ) operating at 108 MHz with 1.5 MW of rf power. Lost beam in the RFQ represents the largest gas load for the vacuum pumps and must be considered in the design. The 2 MeV beam from the RFQ is further accelerated to 10 MeV in 4 m of post-coupler stabilized drift-tube linac (DTL) operating at 216 MHz with 3.5 MW of rf power. The 3 MW proton beam from this 10 m linac will be transported to a carbon beam dump or to a beam analyzing transport line. In addition, the beam, at reduced power levels initially, can be used to study characteristics of heavy metal targets in a liquid metal facility adjacent to the linac. The full 3 MW beam could deposit ∿ 40 kW/cm^2 onto the surface of a liquid metal target.

Plans are now underway to build this $15 M linac, ZEBRA, in a new AECL laboratory to be located in Québec. Approvals to engage a consultant to design the office and laboratory buildings are expected this year with occupancy beginning 1985. ZEBRA should be operational in 1990 at an estimated cost of roughly $35 M when salaries, overheads and pre-ZEBRA study costs are included. Tests for at least ten years have been planned with results feeding directly to the second stage of AB development.

Second Stage

The remaining stages of the AB program would be built at a nuclear park using the team assembled at the new laboratory to oversee design and construction. Although divided into three stages the program has just one facility that is added onto and upgraded following overall program reassessments. The second stage, EMTF (Electronuclear Materials Test Facility), should be completed by the mid 2000's at an estimated cost of roughly $75 M for the 100 m linac and related facilities alone. Beam from the 70 mA, 200 MeV linac will be delivered to a Pb-Bi target that will be used as an experimental facility providing neutron fluxes of 10^{15} n/(s·cm^2) for materials and fundamental research. Reasons for the choice of this energy and current are given elsewhere[4]. The output energy of 200 MeV represents the point at which a change to a more efficient 432 MHz accelerating structure for the higher energy part of an AB would occur.

Beam from the linac could be shared with some of it being used to investigate accelerator characteristics of coupled cavity linacs (CCL) to be used above 200 MeV. EMTF will be designed so that it could be upgraded to accelerate 300 mA of protons by the addition of extra rf stations to the installed 30 MW. This implies that extra rf drive ports, beam diagnostics, control systems, cooling, vacuum, transport elements, shielding and other associated items will have to be considered in the design and construction of EMTF. Beam sharing does not imply continuous beam switching. Because of the high power cw beams involved, the linac must be turned on at low current with the beam directed to a particular area. The beam current would then be increased and operation would continue to a particular area as scheduled.

A third beam usage area for EMTF, not shown in Figure 2, is a target/blanket development area with a 14 MW target, the design of which will be based on experiments with the 3 MW target on ZEBRA. Although the average neutron energy will be 1/2 and the neutrons per proton (1.5 n/p) will be thirteen times less than that of a full AB, the power density in a fuel or blanket element in close proximity to the target will be similar to that of an AB ($\sim$ 0.2 MW/L). This will permit early tests on fuel characteristics including materials properties, swelling, corrosion, embrittlement, radiation creep and growth, and verification of neutronics calculations. Admittedly, the neutron spectrum will not have as large a high energy tail as an AB, but the main spectrum shape will be nearly identical to a 1 GeV spectrum. Highly relevant results particularly on damage questions can be obtained to aid in designing some of the components for the next stage. Some of the beam time could be used to develop the heavy metal target required for an AB.

The reduced EMTF current, 70 mA, is adequate to study most aspects of the DTL portion of an AB. Comparisons with full 300 mA operation of ZEBRA will provide the necessary information to design the last stage of the AB program.

Third Stage

The third stage, to be completed in the mid 2010's, is a pilot facility that will test all aspects of an AB at as low a power level as possible to still provide an acceptable engineering data base that can be used to design and construct a full power AB target/blanket. A 70 MW beam at 1000 MeV into a 150 MW_e target/blanket required for this stage has fortuitously the same current as EMTF. The EMTF Pb-Bi target facility at the 200 MeV location will continue to operate on a shared beam basis with the pilot target/blanket or 70 MW beam dump. Upgrading EMTF to 1000 MeV is expected to cost approximately an additional $500 M including the target/blanket.

A large capital investment in the 140 MW of rf systems means that high efficiency, long lifetime, reliable, and economic rf tubes will be required. Development work on tubes and associated operating systems should be possible for this future need and that of the last stage.

If economic conditions dictate capital savings, the high-grade 430 MW of thermal power need not be converted to electricity by turbine generators, an action that will not jeopardize the effectiveness of the facility. Installation of the rf systems can be organized to spread their capital outlay over several years because the pilot can be operated at low current initially and be gradually upgraded for higher current as rf stations are commissioned. Low current, 10 mA, operation of the pilot linac with blanket material in close proximity to the target will duplicate power densities to be attained by blanket material in the full power AB system. The full power AB target/blanket will have a 100 cm separation between the target and the blanket to purposefully reduce power densities in the blanket.

Fourth Stage

The fourth and final stage consists of adding more rf power stations to the linac and replacing the pilot target/blanket with one designed for 300 MW of beam power. Enough electricity could be generated by the turbine generators attached to the target/blanket to meet the needs of the accelerator and deliver 110 MW_e to the electrical grid. Total cost of an AB is estimated at roughly $1500 M and completion is expected in the mid 2020's. The design of the linac and other components for this facility depends critically on ZEBRA and the experiments and developments that follow this first stage of the development program.

IV RESEARCH, DEVELOPMENT AND DESCRIPTIONS

Research and development work to bring an AB to fruition within the next forty years will include overall system optimizations, studies of competing systems and program reassessments. Work on the accelerator and the target/blanket will require many man years of effort. In the accelerator area, design for and limitations of cw operation will be the major concerns. Beam dynamics theory and other accelerator related computer codes will experience many modifications, improvements and overall developments in the future. Comparisons of calculations and predictions with measurements on injector beam transport, high power beam operation and proton beam acceleration will provide the impetus for change. Significant improvements in beam diagnostics, accelerator control and beam dumps will be required.

Studies for the target/blanket include conceptual designs, fuel management schemes, experiments and calculations. Comparisons of calculated neutron yields and distributions, with experimental measurements at different energies and for different materials, will continue. Determination of fertile to fissile conversion rates are important experiments to be continued using both realistic and simple assemblies. "Scoping" studies that have begun for simple target/blanket configurations will continue with more details being added as more information is acquired.

Target/Blanket

Recent experiments[6] using 100 MeV protons on thick Pb and ^{7}Li targets have shown very good agreement with calculations for Pb (0.34 ± 0.02 n/p) and reasonably good agreement for ^{7}Li (0.12 ± 0.01 n/p) in both the total yield and the axial and radial neutron distributions measured in a large water bath surrounding the target. Scaling these results to 1000 MeV gives the expected neutron yield in Pb of 20 n/p - expected based on measurements at higher energies. Reasonable agreement between calculations and experiments has been obtained with 500 MeV (TRIUMF) and 800 MeV (LAMPF) protons on different target assemblies as summarized in another paper[7] at this workshop. Further work at higher energies will test the suitability of the calculational methods.

The more complex and difficult measurements of fertile to fissile conversion rates need to be continued. Careful analysis and improved techniques must be employed to extract the important data required for designing blankets.

"Scoping" studies[3], of various blanket materials in a target/blanket arrangement that excludes engineering complexities, have been used to give simplified results for a 300 mA, 1000 MeV input proton beam. A liquid metal fast breeder reactor (LMFBR) lattice, simulated by 50% fuel, 25% iron sheath and 25% sodium coolant, was used as shown in Figure 3 except for one set of molten salt cases and one set of cases that mocked a CANDU style lattice. The 100 cm radius cavity was necessary to limit power densities in the blanket to 0.3 MW/L when percentage enrichment in the blanket reached 2% levels. At 2% blanket enrichment, net fissile production rates for ^{233}U from thorium metal, thorium carbide, thorium oxide, thorium oxide CANDU lattice with either H_2O or D_2O coolant, and molten thorium salt were similar at $\sim$ 2 kg per day.

Net production rates of ^{239}Pu at 2% blanket enrichment from uranium metal, uranium carbide, uranium oxide, uranium oxide CANDU lattice and molten uranium salt were 3.6, 3.1, 2.5, 2.2 and 1.8 kg per day, respectively. Fissile fuel production rates calculated for different percentage enrichments were used to determine fuel costs for different proton energies and currents. Figure 4 shows the results of these calculations for production of ^{233}U and ^{239}Pu using the assumptions of an 11% capital charge rate, $17/g reprocessing charges, a facility with 80% availability, and a target/blanket that generates sufficient electricity to meet the needs of the accelerator. Curves of fuel costs are given as a function of incident proton beam energy for different beam powers (production rates are shown at the ends of each curve). At each beam power there is an optimum energy close to 1 GeV that minimizes fuel costs, with the optimum energy increasing slightly for higher beam powers. The accelerator parameters, including frequency, beam aperture and operating gradient, were optimized for each data point on the curves with some cases requiring beam funneling to accommodate the beam currents required. In no case was the frequency multiplication from the RFQ to the CCL allowed to exceed a factor of six. Designs were checked to ensure that rf structures would not break down from excessive field stresses, that ample stored energy was available in the beam region to accelerate the beam and that structure beam loading was not too large.

Figure 4 shows that a slight penalty is incurred for operating at a higher energy than the optimum for fixed beam power. For instance, ^{239}Pu produced from a 300 MW, 2 GeV facility is 11% more expensive than that from a 300 MW, 1 GeV facility. However, the 2 GeV facility would relax some of the accelerator constraints because accelerated current is reduced by a factor of two. The price for ^{239}Pu from a 2 GeV facility with 300 mA of beam, that produces twice the amount of fissile fuel as that from a 300 mA, 1 GeV facility, is only marginally cheaper ($\sim$ 1%).

Fuel costs as a function of production rate in kg per day are shown for 1 GeV protons on a target/blanket producing ^{233}U or ^{239}Pu. Production rate increases as beam current increases with costs beginning to reach an equilibrium level near 4 kg/d for ^{239}Pu and 7 kg/d for ^{233}U. These results suggest that an AB for ^{233}U production should have a higher beam power (factor of 2.5) than that for a ^{239}Pu production facility to minimize costs as much as possible.

Linear Accelerator

A schematic layout of a 300 mA, 1 GeV proton accelerator breeder that would produce sufficient electrical power in the target/blanket to meet the needs of the accelerator is shown in Figure 5. Optimized parameters are shown for a 500 m linac operating at an accelerating gradient of 2.1 MeV/m. A proton linac was selected over a deuteron linac because the marginal increase ($\sim$ 5%) in neutron production at high energies for deuterons is completely overshadowed by difficulties associated with launching the required high current deuteron beam, including such items as structure activation, beam transport, space charge forces and frequency choices.

Accelerator frequency choices were determined as follows. The 6 cm diameter beam bore hole for the CCL (representing 80% of the linac length) was determined from beam dynamics requirements and the need to keep beam spill less than 1 part in 10^5. Optimum structure efficiency for a 6 cm diameter bore is achieved for a structure operating frequency near 450 MHz, a regime easily covered by high power klystron amplifiers. The frequency for the RFQ, the initial part of the linac, was restricted to be as high as possible within the constraints of beam dynamics, rf sources, engineering and rf field breakdown. An operating value of 108 MHz was selected to meet these constraints. These considerations determine rough upper and lower frequency bounds.

The RFQ is an important structure for initial beam acceleration because relatively low (75 kV) injection voltages can be used with improved reliability over 750 kV injectors, the beam is adiabatically bunched improving beam transmission and reducing injector constraints, and rf efficiency is good for acceleration to a modest 2 MeV energy. Frequencies of 216 MHz (x2) and 432 MHz (x4) were selected for following sections of the linac to keep within frequency bounds and to make it possible to use klystron amplifiers for the 216 MHz DTL. Rf structure efficiency for a DTL increases for acceleration of particles with energies greater than 2 MeV and decreases for acceleration of particles with energies above 150 MeV. This is the reason for a change at 200 MeV to a CCL, whose efficiency increases with particle energy.

A heavily beam-loaded linac is a most efficient method for converting rf power to beam power. The design shown in Figure 5 is 80% beam loaded with an ac mains power to beam power conversion efficiency of 56%. Higher beam efficiencies could be obtained if developments in rf sources increased tube efficiencies above the current 70 to 75% levels. Approximately 375 MW of rf power is required in the 500 m accelerator length, resulting in a 1/2 MW rf source every 2/3 m.

The 75 kV proton injector is based on successful high current cw proton injector tests at CRNL that have transported 320 mA of 42 keV protons to beam dumps. Techniques for providing a fully variable output proton beam from zero to full current at fixed energy have been demonstrated for the multi-aperture duoPIGatron ion source. A constraint to be measured on the variable current is that the output emittance must not change.

A breakdown of costs in 1981 dollars for the accelerator breeder shown in Figure 5 is given below.

Target/Blanket	$797 M
Rf Systems	$261 M
Linac	$ 60 M
Controls and Monitoring	$ 36 M
Engineering, Management and 20% Contingency	$298 M
Total	$1452 M

A number of funded pre-ZEBRA activities shown in Figure 6 are underway at CRNL to provide design information for ZEBRA. Developments in ion sources and injector transport on the Ion Source Test Stand (ISTS) and the Injector Test Experiment (ITE) will provide detailed information and operating characteristics for the ZEBRA injector. It has already been decided that a biased RFQ presents more problems than advantages and that a two-stage injector is not required because of techniques developed for providing complete current variability.

Developments for the RFQ are based on 500 MHz RFQ models and a 1 m long 270 MHz sparker. The sparker will be high power tested in early 1983 to determine cw breakdown levels for 36 cm long unmodulated vanes with 5 mm bore radius. Design of a 75 mA, 270 MHz RFQ, RFQ1, that will accelerate protons to 600 keV is underway. Construction of the 50 kV injector should be completed in early 1983. The 2.3 m RFQ construction should be completed in early 1984 with beam tests scheduled for late 1984. Up to 250 kW of rf power will be delivered from the 400 kW triode in operation at CRNL. Experimental tests of RFQ1 will be directed towards confirming predictions of beam dynamics calculations and testing space charge limits.

A cw 3 MeV Alvarez DTL operating at 270 MHz has been accelerating several mA of protons from a 750 kV injector and is being used to determine operation characteristics and engineering details. Construction of an improved replacement tank, 2BLAT, will begin in early 1984. The tank will accelerate 20 mA of protons from 600 keV to 2.2 MeV and will mock the geometry of the first ZEBRA DTL by being a $2\beta\lambda$ design. Eventually it will be used, with RFQ1 as an injector, to study acceleration of an RFQ generated beam. Results from the 3 MeV DTL have been very useful for studying drift-tube stem to outer wall joints, vacuum manifolds, cooling, rf windows and beam monitors as well as operational characteristics.

Three major DTL modeling efforts to determine aspects of post-couplers at 350 MHz, girder-mounted drift-tube suspensions at 480 MHz and coupling loops at 270 MHz are almost complete. Information on post-coupler effects and end-wall terminations was useful for demonstrating how to reduce drift-tube stem currents and how to stabilize relatively small drift-tubes that will incorporate permanent magnets.

A 270 MHz resonant load has been constructed and will begin operation soon to high power test different components for low beta accelerators. This 1 m long aluminum structure, designed to dissipate 400 kW, is an 83 cm diameter cylinder with many ports and flanges to test joints and rf components such as tuners, drift-tubes, windows and post-couplers.

V SUMMARY

Accelerator breeder studies will continue in Canada and will be associated with developments connected with the advanced thorium-cycle CANDU reactor. ZEBRA, the first and most important stage of the AB program, will likely be funded and located at a new laboratory to be sited in the province of Québec. The four stage plan for AB development provides the necessary checks and balances for a program of this magnitude. Reassessment of the overall program goals and directions can be made at intervals using updated information concerning fissionable resources, technology status, power requirements, economics and competing processes.

Good agreement on neutron yields has been obtained between experiment and calculations at 100, 500 and 800 MeV giving some confidence in the calculation methods being used. Further work at higher energies and on conversion rates will be necessary in the future. More detailed work on target/blanket concepts will be required, eventually leading to fuel management schemes.

Work on accelerator developments have been described and should lead to acceptable AB designs. Improvements in rf tube technology could lead to cost savings but not enough to reduce fissile material costs by more than 10%. Improvements in reliability and operation should be the major benefits. Activities underway in pre-ZEBRA activities have provided and will provide useful information for not only the ZEBRA program but for other programs employing cw beams or high power accelerator operation.

AB development offers many years of interesting research within a reasonable time frame. Collaboration with other agencies and laboratories in other countries will be useful. Sharing expertise and resources will benefit everyone involved in high power cw beam operation.

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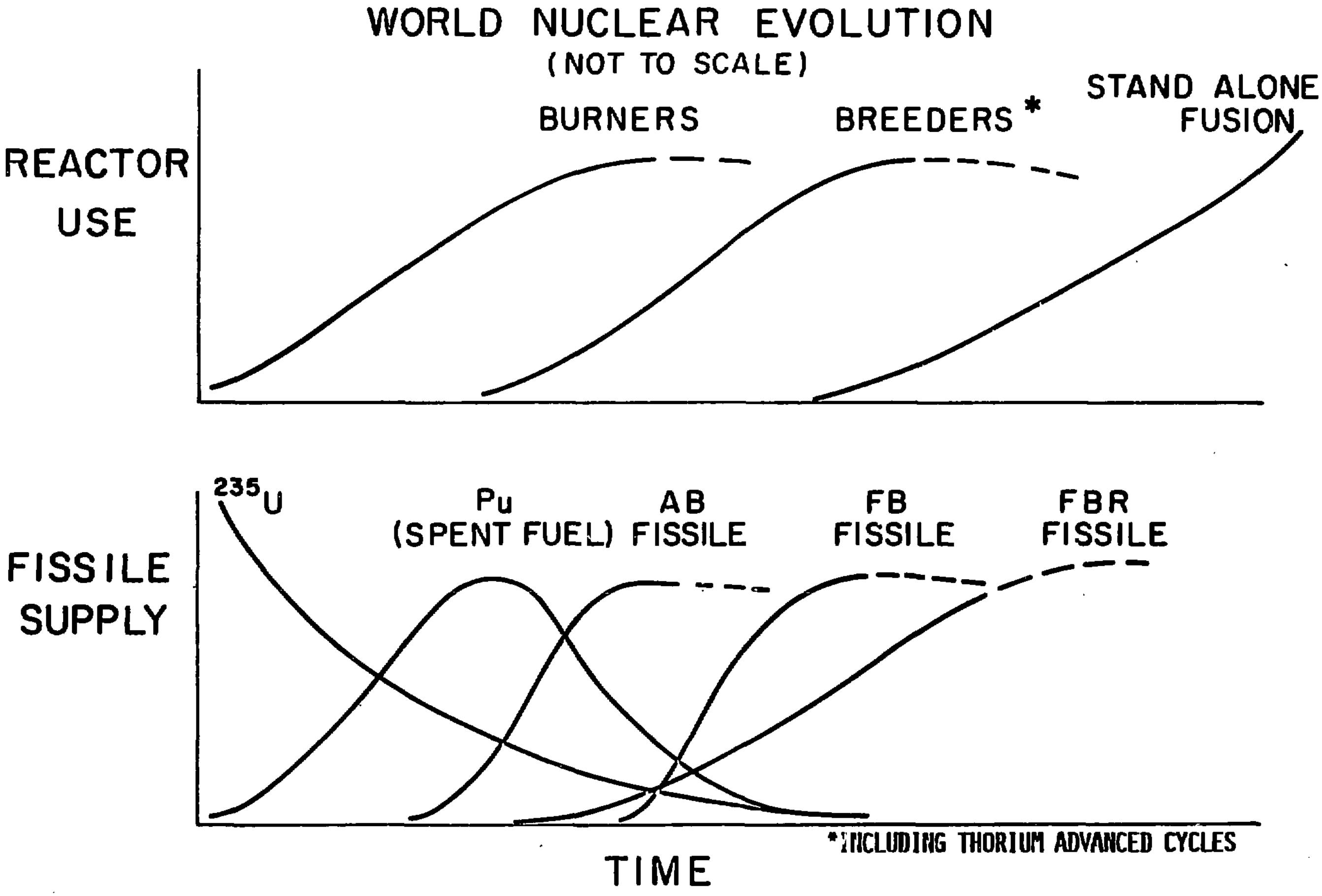


*INCLUDING THORIUM ADVANCED CYCLES

Figure 1 World nuclear evolution and the related fissile supply as a function of time.

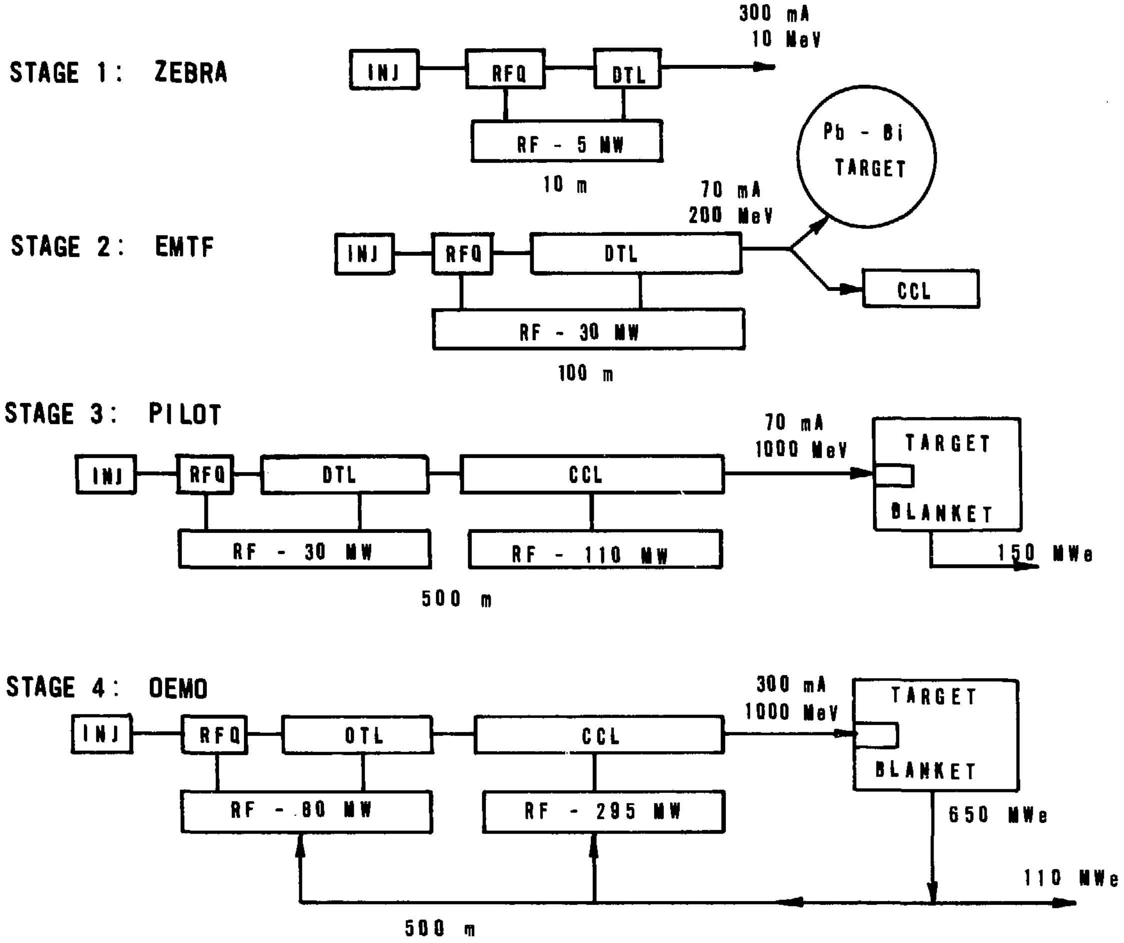


Figure 2 Stages in the development of an accelerator breeder facility.

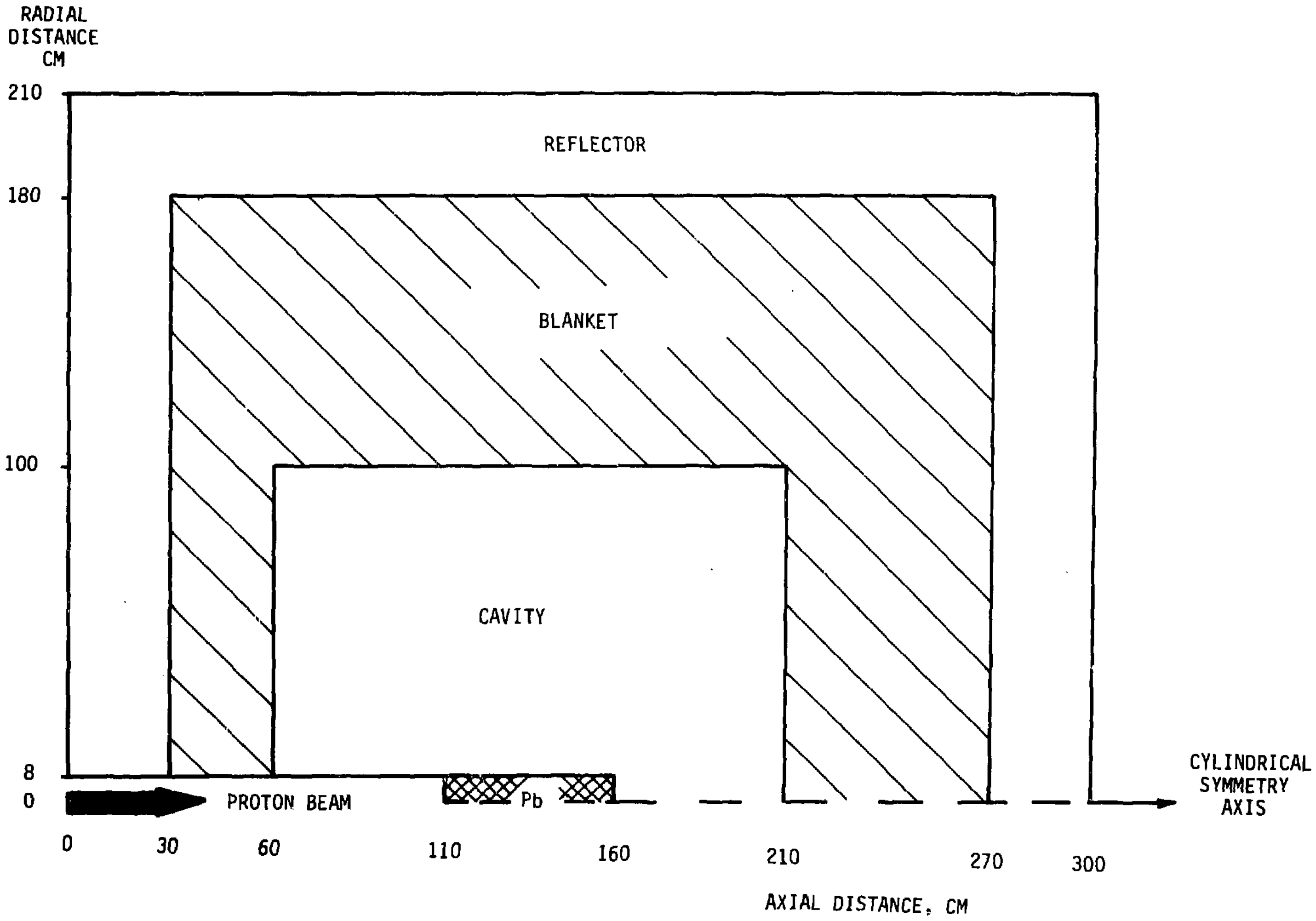


Figure 3 Accelerator breeder target and blanket geometry used for scoping studies.

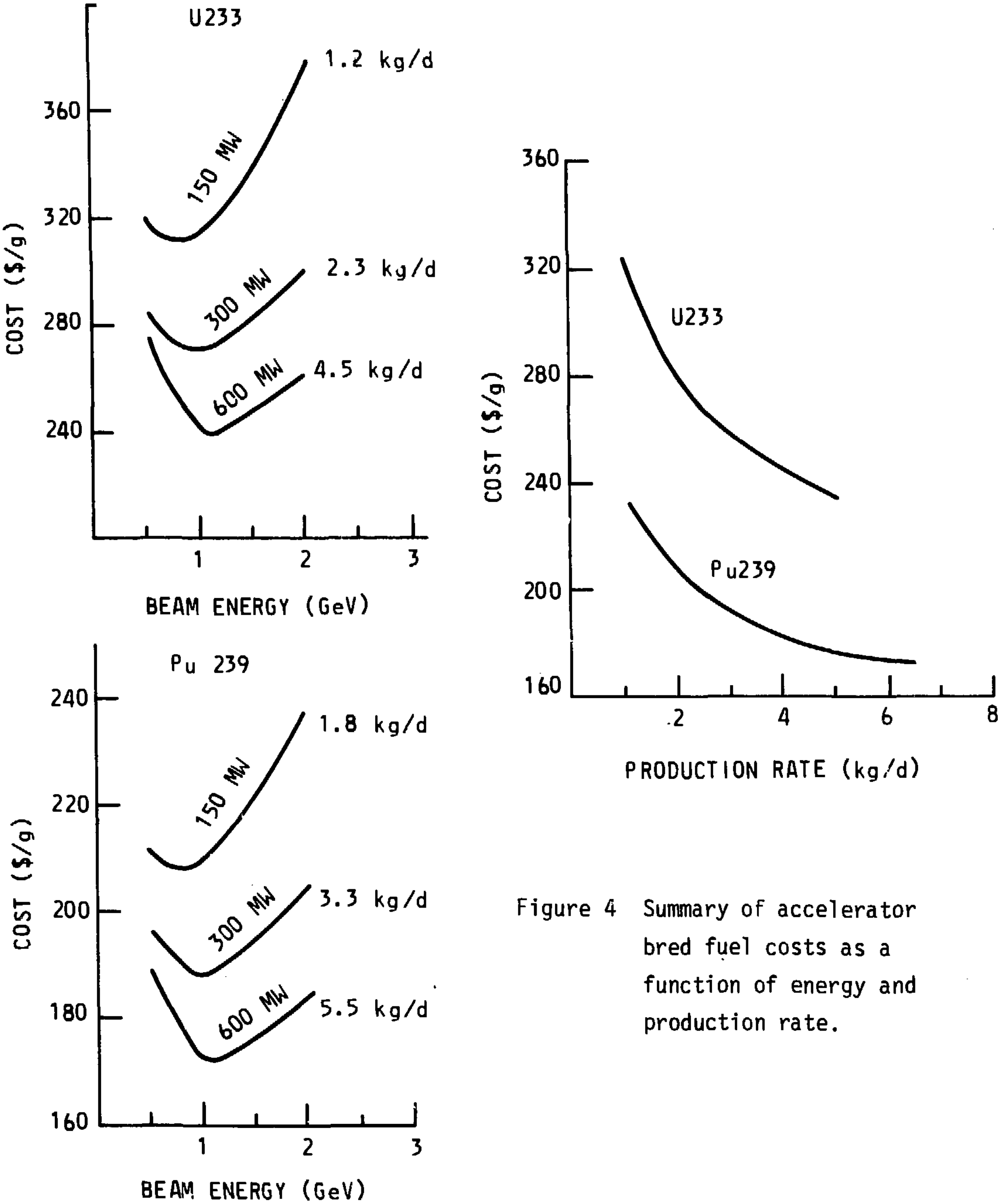
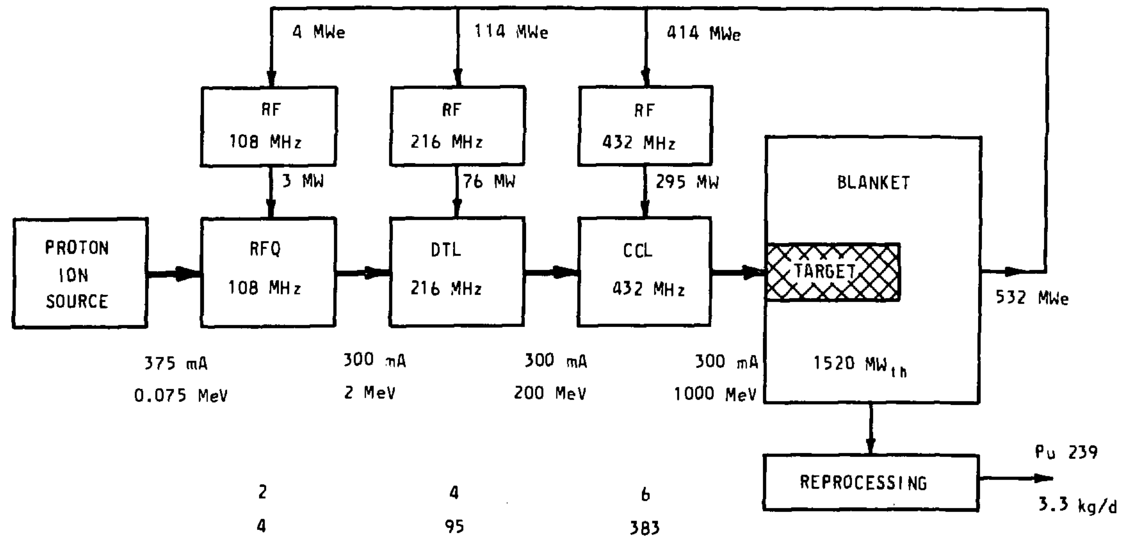


Figure 4 Summary of accelerator bred fuel costs as a function of energy and production rate.



BORE DIA. (cm)		2	4	6	
LENGTH (m)		4	95	383	
SHUNT IMPEDANCE (MΩ/m)			31.3	37.8	
GRADIENT (MeV/m)			2.09	2.09	
COST	$0.8 M	$0.5M	$21M	$73.5M	$797 M(TARGET/BLANKET)
RF COST		$2.0M	$53M	$206 M	

$\underbrace{\hspace{6cm}}_{\$357M}$

Figure 5 Schematic of an accelerator breeder that is energy self-sufficient.

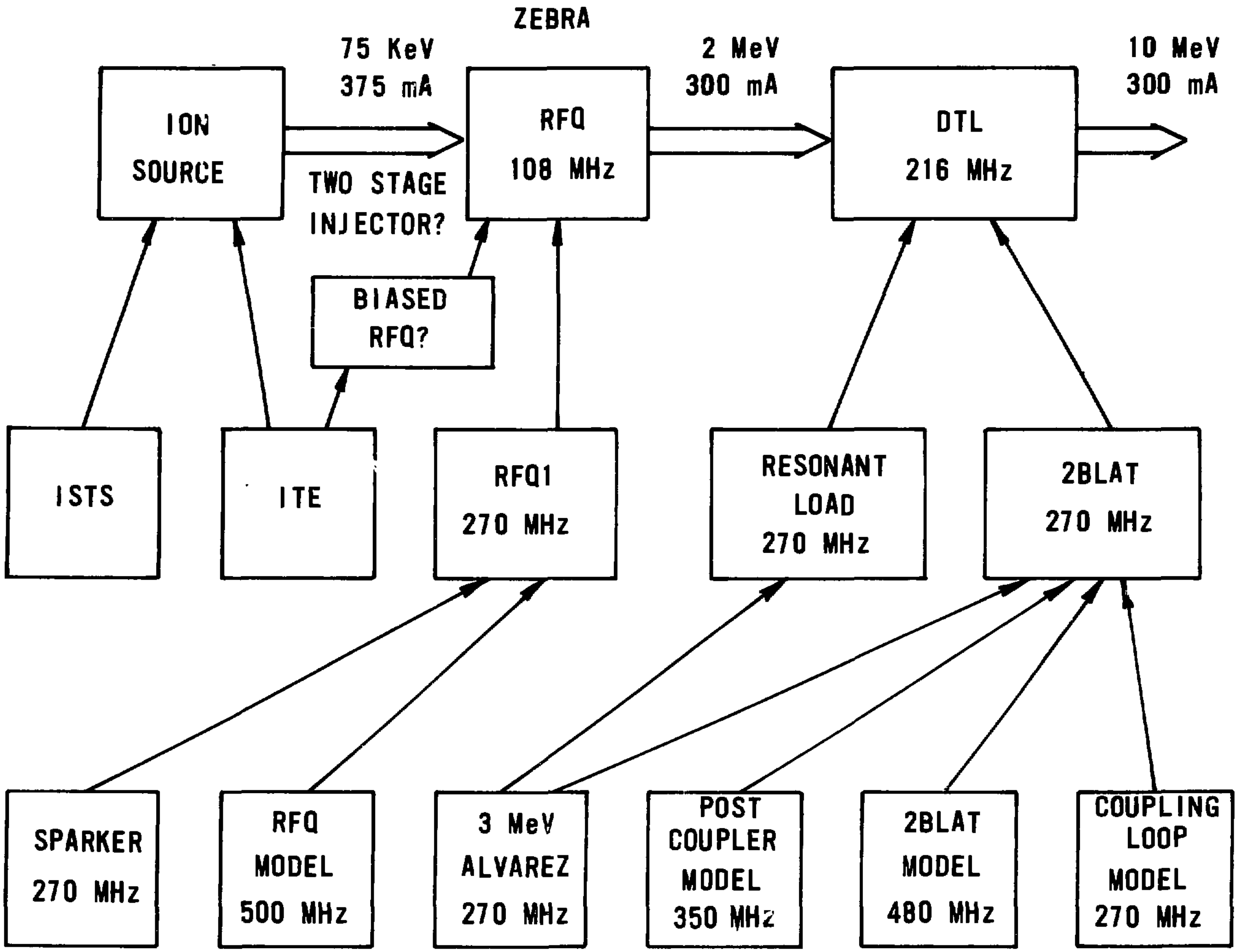


Figure 6 Pre-ZEBRA activities leading to the ZEBRA system.

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