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PREFACE

This report contains extensive information on the past uses of the Oak Ridge Electron Linear Accelerator (ORELA) and future research plans for the facility. It also contains information on facility operation and options for improvement. Although possibilities for replacement of the electron accelerator with a proton accelerator are discussed, this report was not intended to serve as a justification for such a conversion. Because of the variety of coverage, the authors anticipate that most readers will wish to read only the summary and those specific sections of immediate interest.

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ABSTRACT

This report reviews the accomplishments of the first decade of operation of the Oak Ridge Electron Linear Accelerator (ORELA) and discusses the plans for the facility in the coming decade. Motivations for scientific and applied research during the next decade are included. In addition, ORELA is compared with competing facilities, and prospects for ORELA's improvement and even replacement are reported. Development efforts for the next few years are outlined that are consistent with the anticipated research goals. Recommendations for hardware development include improving the electron injection system to give much larger short-pulse currents on a reliable basis, constructing an Electron Beam Injector Laboratory to help make this improvement possible, continuing a study of possibly replacing the electron accelerator with a proton machine, and replacing or upgrading the facility's data-acquistion and immediate-analysis computer systems. Increased operating time and more involvement of nuclear theorists are recommended, and an effective staff size for optimum use of this unique facility is discussed. A bibliography of all ORELA-related publications is included.

ACRONYMS

BES	Basic Energy Sciences program of DOE's Office of Energy Research
CBNM	Central Bureau for Nuclear Measurements, the cooperative European laboratory near Geel, Belgium
CSEWG	Cross Section Evaluation Working Group
DAC	Data Acquisition Computer
DNA	Defense Nuclear Agency
DOENDC	Department of Energy Nuclear Data Committee
ENDF	Evaluated Nuclear Data File (U.S.)
EPRI	Electric Power Research Institute
FBR	Fast Breeder Reactor
FMIT	Fusion Material Irradiation Test Facility
FOM	Figure of merit, for various pulsed-neutron sources
GELINA	Electron linear accelerator at the Central Bureau of Nuclear Measurements near Geel, Belgium, funded cooperatively by the European governments
HELIOS	New electron linear accelerator at Atomic Energy Research Establishment, Harwell
HTGR	High Temperature Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
IBR2-LIU30	The IBR-2 is the pulsed reactor in Dubna, USSR; with the LIU30 linear induction accelerator, it would be used as a booster with modulated reactivity
INDC	International Nuclear Data Committee
JAERI	Japan Atomic Energy Research Institute, at Tokai-Mura, Japan
JINR	Joint Institute for Nuclear Research, USSR
kerma	Kinetic energy release in material from incident radiations (j/kg)
KFK	Kernforschungszentrum Karlsruhe in Federal Republic of Germany
LAMPF	Los Alamos Meson Production Facility at LANL
LANL	Los Alamos National Laboratory
LLNL	Lawrence Livermore National Laboratory
LMFBR	Liquid Metal Fast Breeder Reactor
LWR	Light-Water Reactor
MIT	Massachusetts Institute of Technology

NASAP	Nonproliferation Alternative Systems Assessment Program of DOE
NBS	National Bureau of Standards
NNDC	National Nuclear Data Center
OMFE	Office of Magnetic Fusion Energy
ORELA	Oak Ridge Electron Linear Accelerator
ORNL	Oak Ridge National Laboratory
PIGMI	Pion Generator for Medical Irradiations, a documented LANL accelerator design
PSR	Proton Storage Ring, a LANL Project at LAMPF
RFQ	Radio Frequency Quadrupole, a type of first-stage particle accelerator
RPI	Rensselaer Polytechnic Institute
SLAC	Stanford Linear Accelerator
TOF	Time of flight
WNR	Weapons Neutron Research Facility attached to LAMPF at LANL

SUMMARY

The Oak Ridge Electron Linear Accelerator (ORELA) is an experimental facility dedicated to the study of the interaction of neutrons with nuclei by "time-of-flight (TOF)" techniques. The experiments utilize a pulsed source of neutrons generated when pulses of electrons from the accelerator impinge upon and interact with a centrally located target. Neutron flight paths (tubes) extend radially from the target, and the energies of the neutrons detected at experimental stations along the flight paths are determined from the times required for them to "fly to" the stations. With a number of experimental stations available, together with data-acquisition and immediate-analysis systems that can process large volumes of data, several TOF experiments can be performed simultaneously.

When ORELA first became a productive measurement facility in 1970, its research staff embarked upon an ambitious program with two overlapping goals: (1) to provide the "applied" neutron cross sections and related data needed for nuclear systems that were under design or being considered for design; and (2) to engage in basic physics studies that would lead to a fuller understanding of neutron-nucleus interactions and nuclear structure. At the time, the staff was already experienced in neutron cross-section research and was cognizant of specific data needs. In this report we celebrate and document the significant gains that have been made toward both goals during ORELA's first decade of operation -- gains that have been made possible primarily through the financial support of the Department of Energy's Office of Basic Energy Science and its antecedent agencies. Important additional support toward the first goal has also been provided by the DOE Office of Reactor Research and Technology, and support for specific measurements has been provided by the Defense Nuclear Agency.

In addition to reviewing ORELA's accomplishments in this report, we suggest worthwhile approaches now indicated for future research at the facility. Finally, we discuss improvements that would permit this research to be carried out more effectively.

Data for Application to Nuclear Systems (The First Decade). -- In ORELA research aimed at meeting the first goal cited above, measurements have been made on almost every type of neutron reaction of interest in the energy range in which it is important for the analyses of nuclear systems. The most studied reactions have been those considered important for calculations of neutron transport in radiation shields, neutron and fuel economics, the effects of depletion and transmutation on discharged materials, and radioactivation. The emphasis has been both on the materials now employed in fission reactors and on those proposed for use in fusion reactors. Relevance is assured through sponsor contact, through the national infrastructure set up to codify neutron data needs, through cooperation with nuclear analysts in a building adjacent to ORELA, and through normal professional interchange of ideas. The broad range of data and its correspondingly high quality have resulted in a significant enrichment of neutron cross-section libraries, including the official U.S. Evaluated Nuclear Data File (ENDF/B).

Basic Nuclear Physics Data (The First Decade). -- The basic physics studies at ORELA -- those directed toward the second goal -- have been numerous and diverse. The intensity, stability, and energy resolution available at the facility are essential for basic studies of neutron partial and total capture cross sections and of neutron scattering and total

cross sections. Fission resonances have been studied with polarized neutrons and polarized target nuclei. Resonances excited by p- and d-wave neutrons in the kiloelectron volt range can now be clearly resolved, and analysis of these resonances has broadened our information on level densities and strength functions. Systematic studies of neutron capture for over a hundred nuclides have allowed better estimates of slow-process nucleogenesis in nuclear astrophysics. Properties of bound as well as unbound states have been studied, the unbound states including those of the "second well" that influences the cross sections of the fissionable nuclides. Important nuclear properties have been explored and quantified more thoroughly with ORELA than had previously been possible.

Condensed Matter Research. -- Although condensed matter research has never been a stated goal for ORELA, the facility can compete with established reactor beam installations for such research when the excitations to be studied require neutrons as energetic as one-half electron volt. During this first decade, a few such studies have been performed at the facility.

Future Nuclear Data Needs for Reactor Programs. -- The need in the future for efficient fission and fusion nuclear energy devices implies the need for at least another decade of cross-section measurements devoted to the first goal. In addition to being needed for calculations of specific designs, codified nuclear data based on experiment are required for survey studies and for the use of fusion and fission (and hybrid) test devices and power systems of every category. Nuclear data are also required for the design of facilities for the handling and storage of spent fuel from fission reactors. During the coming decade of consolidation in the fission reactor industry, improved data should have strong influence on fuel efficiency and cost in future reactor use. In the fusion area, proof of feasibility will be more important than cost minimization. To support the fusion efforts, ORELA will undoubtedly be called upon to measure quantities not yet studied at the facility. The combination of incentives for fusion and fission systems will justify a continued strong push to achieve a complete and accurate set of cross-section data for nuclear applications.

Future Basic Nuclear Physics Research. -- As the second goal is pursued in the future, the basic physics information that will be obtained in ORELA experiments will clarify and extend the gains of the past, particularly if the effective energy resolution of ORELA can be improved and additional isotopic samples can be obtained. Increased interaction with nuclear theorists to exploit the available data is expected. Areas for expanded study include studies of the distribution of proton and alpha widths in low-energy resonances, the systematics of fission barriers, the identification of various doorway states, and the variations in partial neutron capture widths. Neutron studies have always provided a unique "window" through which to view in fine detail the nuclear level properties in the binding energy region several MeV above the ground state. As the quality and size of this window are extended by improved instrumentation, and as our ability to plan critical observations is enhanced by improved nuclear physics understanding, the value of studies using this window will continue to increase.

History of ORELA Performance and Development. -- Typical ORELA experiments require one to ten weeks of data acquisition with appropriate flight path lengths, pulse repetition rates, and electron burst widths. Demand for scheduled time in principal investigator status has led to typical experiment backlogs of 10 to 12 months, even though several flight paths are available. For these reasons, ORELA operation has stressed reliability as well as intensity. Operating schedules were originally 12 continuous days during a 14-day period, but as an economy measure they are now 10 continuous days per 14-day period.

Periods of strong performance have demonstrated the capability of ORELA to deliver 60 J of electron power per pulse to the target at repetition rates of 1000 pulses per second (pps) with pulse widths as narrow as 24 ns. Power for short pulses (~5 ns) usually has not been correspondingly high because of below-design performance of the triode electron gun or the nonlinear "breaking wave" pulse-forming circuitry that drives its cathode. A small but effective development effort has solved some of these problems. The largest single effort has been to add a complex macropulse buncher to the electron injection system to increase the short-pulse current through compression of an ~15-ns pulse from the electron gun. However, faulty original components, as well as intrinsic difficulties, have so far prevented use of this system. Thus, though extensive periods of full-strength operation have assured ORELA's position as the leading pulsed source for neutron physics studies, for other extensive periods the output has not reached design levels. For the experiments most demanding of intensity, it has therefore sometimes been necessary either to accept somewhat poorer signal-to-background ratios than planned or to accept degraded energy resolutions.

In addition to dependence on the accelerator performance, the research output of the facility is also dependent on the instrumentation and data-acquisition equipment available to the experimenters. Innovative fission chambers, flux monitors, and other detectors have been developed, and new ideas always await trial. Outstanding data-acquisition and analysis computer systems have also been developed and extended, but some of the present computer equipment has now become obsolete.

Future Facility Improvements. -- As experiments are considered that will require increased intensity, narrower energy resolution, and higher energy neutrons, it is apparent that maximum ORELA performance will be required. Examples of such experiments are measurements of (n,p) and (n,α) reactions in the MeV region and extension to higher energy of the detailed resonance analysis of total cross sections and capture gamma-ray spectra. To meet this challenge, the ORELA staff is considering options to enhance the performance of the present machine and the associated data-handling equipment. The possibility of replacing ORELA with a proton accelerator is also being considered, using technology that was not available when ORELA was built. Study of the improvement options has led to the recommendations summarized below:

(1) Adding an Electron Beam Injector Laboratory. -- Reliable injector operation must be obtained for at least the ~15-A peak currents long shown to be feasible. One necessary step is to acquire more reliable gun-pulsing electronics. Another is to establish adequate laboratory facilities for the fabrication and thorough evaluation of electron guns prior to their installation on the machine. Efforts to complete the electron pulse buncher system should also be continued to increase the short-pulse intensity, and test facilities for the entire injector system should be provided. Therefore, an Electron Beam Injector Laboratory is proposed as an addition to the second floor of the ORELA building to provide appropriate spaces for electron gun production and injector system testing.

(2) Obtaining High-Efficiency Klystrons. -- It should be determined whether the klystron design used for ORELA can be modified to obtain higher efficiency. The Stanford Linear Accelerator staff has succeeded in producing high-power klystrons (for higher frequencies) with 40 percent higher efficiency than is obtainable with the tubes used at ORELA. A goal of a 40-MW peak power per tube with 55 percent efficiency may be attainable using the present pulsed power supplies.

(3) Giving Further Study to Replacing ORELA. -- The study of the options for replacing ORELA should be completed. Studies of a proton linac replacement have indicated that the acceleration of single microbursts of protons would be quite expensive if the goal is to produce four times as many neutrons per pulse as is possible with the current machine. However, other approaches should be reviewed to determine whether an attractive option does exist.

(4) Updating Data Acquisition Computers. -- Though efficient and productive, the facility's data-acquisition computers are becoming obsolete and need to be replaced with more modern devices that would allow larger data storage arrays, higher ultimate data accumulation rates, and improved servicing of experiments.

(5) Updating Immediate Data Analysis System. -- The DEC-10 computer system used for the immediate analysis of ORELA data is obsolete and will gradually become difficult to maintain. Replacing this computer system is proposed if compatibility with most of the existing software can be established.

Beyond the hardware improvements discussed above, it is suggested that improvements in operation and staffing be made as follows:

(1) Resuming Operation 12 Days per 14-Day Cycle. -- The facility productivity would be significantly increased if the operation schedule were changed from the 10 days per 14-day cycle back to the earlier schedule of 12 days per 14-day cycle. (The productivity improvement with this change would be second only to that realized by increasing the output and reliability of the electron injector system, as described above.)

(2) Increasing Involvement of Nuclear Physics Theorists. -- Now that basic physics studies have yielded copious results in several study areas, increased involvement of nuclear physics theorists is desirable and should continue to be stimulated with workshops, seminar series, joint projects, etc.

(3) Increasing Number of Facility Users. -- ORELA is capable of supporting a larger experimental research effort. This goal could be accomplished by increasing the number of technical assistants available to the staff or increasing the research staff itself. The latter could be accomplished with little increase in local operating costs by increasing the number of outside scientists who collaborate with ORELA staff.

During its first decade of operation, the ORELA facility has fulfilled the expectations of its founders in the extent and quality of its product. Consistent performance of ORELA near its maximum output is required to fully meet the challenge of demanding future experiments toward both applied and basic physics goals, and major facility upgrades need to be considered. As the requirements for and capabilities to use detailed neutron data increase, careful planning is required to assure maximum value from the unique ORELA facility.

I. INTRODUCTION

The Oak Ridge Electron Linear Accelerator (ORELA) was designed, fabricated, and brought into operation during the same time period -- 1966-1969 -- that several other U.S. electron linacs came on line (at LLNL, NBS, and MIT). In general, each linac was designed for a specific type of measurement. For ORELA the criterion was to provide a facility that had a high-performance pulsed source of neutrons and could simultaneously support a number of experiments to study neutron interactions in various materials. At the resulting facility, illustrated in Fig. 1, the neutrons are produced when pulses of electrons impinge on a target. The neutrons travel along flight paths emanating outward from the target room, and their energies are determined from the times required for them to reach the given experimental stations.

The funding for the construction and operation of ORELA primarily has come from the DOE Office of Energy Research (Basic Energy Sciences Program) and the DOE Division of Reactor Research and Technology and their predecessor organizations. The interests of the Office of Energy Research have been to obtain nuclear physics data that can best be derived from measurements of neutron interactions, emphasizing projected long-range data needs. Within this broad field have been subprograms to provide nuclear data on actinide elements produced in reactors and to meet the nuclear data needs of the magnetic fusion energy program. The interests of the Division of Reactor Research and Technology have been to measure and evaluate neutron interaction cross-section data essential to advanced reactor design. In addition to these two DOE sponsors, the DOD Defense Nuclear Agency has funded measurements and evaluations of neutron cross sections in which the agency has a particular interest.

The various experiments performed at ORELA during the last decade have promoted much scientific interchange with its many associated benefits. The ORELA staff has collaborated with numerous visiting scientists in diverse research efforts (see Appendix A), and the large body of "applied" nuclear data obtained at the facility has resulted in continued interaction of the staff with the U.S. Cross Section Evaluation Working Group (CSEWG) and with international nuclear data bodies. In addition, informal interactions with other ORNL nuclear physicists and with local analysts in reactor physics and shielding are always ongoing. With respect to the practical application of nuclear data, the importance of cooperative efforts among the measurers, evaluators, processors, and users can scarcely be exaggerated. Ideas on such applications, and also on new ORELA research, are frequently exchanged within the Division of Nuclear Physics of the American Physical Society, as well as within other national and international groups.

The purpose of this report is to plan for ORELA's future -- up to 1995. The plans fall into two categories: (1) plans for future experimental investigations; and (2) plans for improving the facility. In the first category, we attempt to identify systems whose projected designs will require specific nuclear data and also to predict the directions in which basic nuclear physics research should move. In the second category, we explore the possibilities for enhancing the performance and usability of ORELA's pulsed source of neutrons.

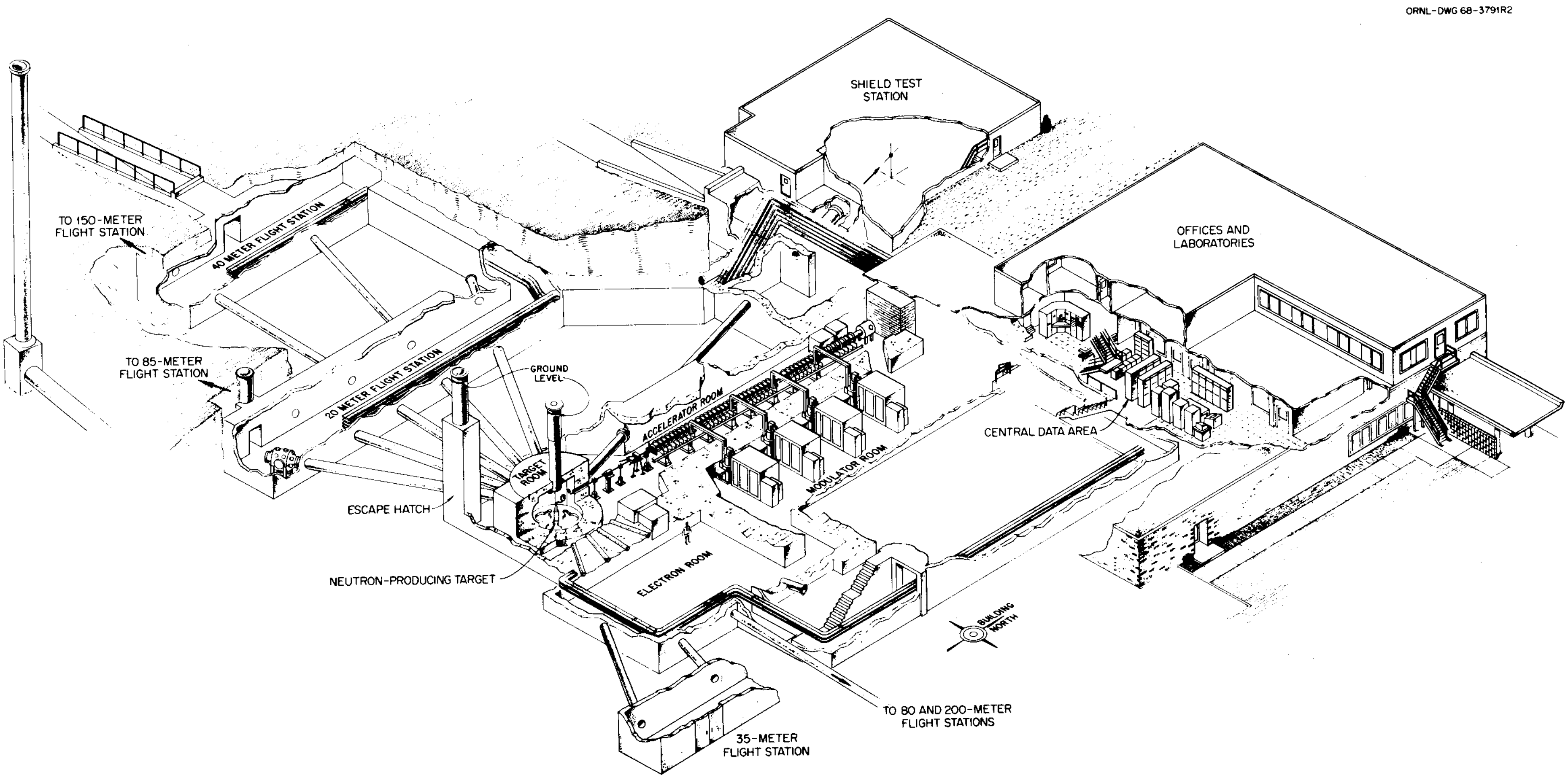


Fig. 1. Flight-Path Layout at ORELA. Note that the flight paths and experiment stations are predominately below the ground surface.

The future, of course, always builds on the past, and in order to plan for the next decade at ORELA we must be familiar with the work that has been accomplished to date. Thus the first several sections of this report summarize the measurements made since 1970 and report on ORELA's performance during the same time period. A bibliography of journal articles and reports describing the work is presented in Appendix B. A review of these sections not only confirms the foresight of ORELA's founders but also inspires confidence that in the future ORELA will make even more valuable contributions to science.

II. THE FIRST DECADE - DATA FOR APPLICATION TO NUCLEAR SYSTEMS

A. Introduction

During ORELA's first decade of operation, the acquisition of "applied" nuclear data required for the design and/or analysis of specific types of nuclear systems has been a primary goal. The systems have included fission reactors (with emphasis on fast reactors), fusion devices, and systems pertinent to the study of weapons radiation transport. The results have profoundly impacted the national nuclear data reference set (ENDF/B), with the body of available nuclear data greatly enlarged and improved.

B. Fission Reactor Programs

For fission reactor programs, measurements have been made of the important cross sections and related parameters of the fissile and fertile nuclides that comprise the reactor fuel (^{235}U, ^{238}U, ^{239}Pu, and ^{240,241}Pu), the measurements spanning the neutron energy range from thermal to a few hundred keV. The higher energy range (from about 1 keV to several hundred keV) is of primary importance to fast reactors and the lower range (from thermal to about 1 keV) is of most importance to thermal reactors. Except for measurements made in the USSR, the ORELA measurements, together with some obtained earlier in a cooperative ORNL-RPI program, have provided the only high-resolution data on the resonance capture cross sections of the fissile nuclides.

The types of applied nuclear data on the fissile and fertile nuclides that have been published by the ORELA staff are shown in Fig. 2. The specific measurements on these and other heavy mass nuclides, including transplutonium nuclides, are listed in Table 1. Table 1 also gives an indication of the impact of the various measurements on the ENDF/B Data Set. (The nuclides in the boxes in dashed outline in Fig. 2 have such short half-lives that their cross sections are relatively unimportant for nuclear energy applications.)

Nuclear data for nuclides other than fissile and fertile materials are also important for reactor design and analysis -- for example, those nuclides included in structural, coolant, and shielding materials. In addition, it is important to have nuclear data on the fission products since their presence must be accounted for in core physics calculations. Table 2 lists the measurements on these types of materials that have been performed at ORELA. For the nuclides present in structural and coolant materials and in the fission products, neutron capture is the most important reaction on which data are needed. For the nuclides in shields, the primary cross sections of concern are those for total interactions, scattering, and neutron and gamma-ray production.

Tables 1 and 2 illustrate the versatility of ORELA for many types of measurements.

C. Fusion Device Programs

ORELA measurements have also made a significant impact on the nuclear data needs of fusion device programs (La80). Essentially all of the requests for cross sections describing the production of gamma rays by neutron interactions in the 700-keV to 20-MeV

Table 1. ORELA Measurements on Reactor Fuel Nuclides

			ENDF Impact			
Nuclide	Type of Measurement	Neutron Energy Range	Strong	Substantial	Weak	Too Recent
^{231}Pa	Total cross section	0.5 - 100 eV				X
	Fission cross section	0.3 eV - 12 MeV				
^{232}Th	Total cross section	0.008 eV - 40 MeV				X
	Fission cross section[a]	0.7 - 10 MeV				X
	Capture cross section	20 eV - 0.8 MeV		X		
	Gamma production	0.2 - 20 MeV				X
^{233}U	Total cross section	0.01 - 2.0 eV				X
	Fission cross section[b]	0.02 - 2000 eV	X			
	Capture cross section[b]	0.02 - 2000 eV	X			
	$\bar{\nu}$ (neutrons per fission)	500 eV - 6 MeV				X
^{235}U	Fission cross section	0.01 eV - 100 keV	X			
	Capture cross section	0.01 eV - 100 keV	X			
	$\bar{\nu}$ (neutrons per fission)	0.01 eV - 10 MeV				X
	Resonance spin assignments[c]	1.1 - 300 eV			X	
^{238}U	Total cross section	5 eV - 100 keV	X			
	Fission cross section	5 eV - 3.5 keV			X	X
	Capture cross section	5 eV - 100 keV	X			
	Inelastic scattering	82 keV				X
	Inelastic-scattering gamma-ray yields	0.5 - 5 MeV				X
^{237}Np	Total cross section	0.5 eV - 100 keV				X
	Capture cross section	0.01 eV - 200 keV				X
	Resonance spin assignments	1.5 - 88 eV			X	
^{239}Pu	Total cross section	300 eV - 10 keV	X			
	Fission cross section	0.01 eV - 200 keV		X		
	Capture cross section	0.01 eV - 200 keV	X			
	$\bar{\nu}$ (neutrons per fission)	0.01 eV - 10 MeV				X
^{240}Pu	Total cross section	2.5 eV - 6 MeV				X
	Fission cross section	20 eV - 20 MeV	X			X
	Capture cross section	0.01 eV - 200 keV	X			
	$\bar{\nu}$ for spontaneous fission					X
^{241}Pu	Fission cross section	0.01 eV - 30 keV		X		
	Capture cross section	0.01 eV - 250 keV	X			
^{241}Am	Fission cross section	0.003 eV - 18 MeV				X
	Capture cross section	0.01 eV - 37 keV	X			
^{242m}Am	Fission cross section	0.02 eV - 10 MeV				X
^{243}Am	Total cross section	0.5 eV - 1000 eV		X		
^{243}Cm	Fission cross section	0.4 eV - 2 MeV				X
^{244}Cm	Total cross section	0.5 eV - 400 eV				X
^{245}Cm	Fission cross section	0.4 eV - 2 MeV				X
^{248}Cm	Total cross section	0.5 eV - 100 eV		X		
^{249}Bk	Total cross section	0.5 eV - 100 eV				X
^{249}Cf	Total cross section	0.5 eV - 100 eV				X
	Fission cross section	0.02 eV - 1.5 MeV		X		
^{252}Cf	$\bar{\nu}$ for spontaneous fission			X		X

[a]Fission fragment angular distributions have also been observed.

[b]ORNL-RPI measurements.

[c]Potentially, the impact of these spin assignments on ENDF/B is large. The fission cross section in the unresolved resonance energy region has also been separated according to the spin of the compound states that result from the absorption.

Table 2. ORELA Measurements on Structural, Shielding, and Fission-Product Nuclides*

Nuclide	Total Cross Section	Capture Cross Section	Gamma-Production Cross Section	Other
^{6}Li	10 eV - 20 MeV (1)			(n,α), 70 - 3000 keV (2)
^{7}Li	0.1 - 20 MeV (R)	2.6 keV - 1 MeV	0.5 - 5 MeV	(n,xn), 1 - 20 MeV
^{9}Be		2.6 keV - 1 MeV (N)		
C	0.2 - 80 MeV (2)	150-keV resonance (3)	Thresh - 20 MeV (1)	
N			Thresh - 20 MeV (1)	(n,p), (n,α), 0.5 - 15 MeV (R)
^{16}O	0.2 - 80 MeV (2)	434-keV resonance (3)	Thresh - 20 MeV (3)	
F	5 eV - 20 MeV (1)	2.6 keV - 1 MeV (2)	0.6 - 20 MeV (1)	
^{23}Na	0.032 - 37 MeV (1)	3 - 600 keV (1)	0.2 - 20 MeV (1)	(n,n'γ), 0.44 - 2 MeV (1) (n,n), 0.5 - 2 MeV (1)
Mg†	0.009 - 39 MeV (1)	2.6 keV - 2 MeV (3)	0.6 - 20 MeV (1)	
^{27}Al	0.025 - 80 MeV (2)	2.6 keV - 1 MeV (2)	0.6 - 20 MeV (1)	(n,n'γ), 0.6 - 20 MeV (2) (n,xn), 1 - 20 MeV (R)
Si†	0.025 - 80 MeV (2)	2.6 keV - 1 MeV (3)	0.6 - 20 MeV (1)	(n,n'γ), 1.78 - 4 MeV (1)
^{31}P		2.6 keV - 1 MeV (R)		
S†	0.025 - 5 MeV	2.6 keV - 1 MeV (R)		(n,α), 10 - 700 keV (R)
Cl	50 eV - 20 keV (R)	2.6 keV - 1 MeV (R)		
Ca†	0.2 - 80 MeV (2)	2.6 keV - 1 MeV (2)	0.6 - 20 MeV (1)	
Ti	0.02 - 30 MeV (R)	2.6 keV - 1 MeV (3)	0.3 - 20 MeV (R)	(n,xn), 1 - 20 MeV (R)
V		2.6 keV - 1 MeV (3)	0.2 - 20 MeV (1)	
Cr†	0.2 - 20 MeV (1)	2.6 keV - 1 MeV (1)	0.6 - 20 MeV(2)	
^{55}Mn		2.6 keV - 1 MeV (2)	0.2 - 20 MeV (1)	
Fe†	0.2 - 80 MeV (1)	2.6 keV - 1 MeV (1)	0.6 - 20 MeV (1)	(n,n'γ), up to 2 MeV (2) (n,n), 0.04 - 20 MeV (1)
^{59}Co		2.6 keV - 1 MeV		
Ni†	0.2 - 80 MeV (2)	2.6 keV - 1 MeV (R)	0.6 - 20 MeV (1)	
Cu†	0.2 - 80 MeV (1)	2.6 keV - 1 MeV (R)	0.6 - 20 MeV (1)	(n,xn), 1 - 20 MeV (R)
Zn†			0.85 - 20 MeV (N)	
^{86}Kr	50 eV - 500 keV (R)	2.6 keV - 1 MeV (R)		
Zr†		2.6 keV - 1 MeV (2)		
^{93}Nb	0.025 - 30 MeV (R)	2.6 keV - 1 MeV (2)	0.65 - 20 MeV (3)	(n,xn), 1 - 20 MeV (R)
Mo	0.025 - 80 MeV (R)	2.6 keV - 1 MeV (2)	0.2 - 20 MeV (3)	
Ru†		2.6 keV - 1 MeV (N)		
^{103}Rh		2.6 keV - 1 MeV (R)		
Pd†		2.6 keV - 1 MeV (R)		
Ag			0.3 - 20 MeV (N)	
Cd		2.6 keV - 1 MeV (2)		
Sn†	1 - 80 MeV (R)		0.75 - 20 MeV (N)	
Te		2.6 keV - 1 MeV (N)		
I		2.6 keV - 1 MeV (N)		
^{133}Cs		2.6 keV - 1 MeV (R)		
Ba		2.6 keV - 1 MeV (2)		
La,Ce,Pr,Nd		2.6 keV - 1 MeV (N)		
^{181}Ta		2.6 keV - 1 MeV (R)	0.6 - 20 MeV (1)	Bound level structure data, 0.1 MeV < E_x < 2 MeV
^{182,3,4,6}W		2.6 keV - 1 MeV (R)	0.6 - 20 MeV (1)	
^{197}Au	0.025 - 80 MeV	2.6 keV - 1 MeV (1)	0.2 - 20 MeV (N)	
Pb	1 - 80 MeV (R)	2.6 keV - 1 MeV (1)	0.5 - 20 MeV (1)	
^{206}Pb	15 - 900 keV (R)	2.6 keV - 0.6 MeV(1)		Relative differential scattering (same range as total)
^{207}Pb	10 - 500 keV (R)	2.6 keV - 0.7 MeV (1)		Relative differential scattering (same range as total)
^{208}Pb	0.03 - 3 MeV	2.6 keV - 0.7 MeV (R)		
^{209}Bi	50 eV - 0.5 MeV	2.6 keV - 0.7 MeV		

*Numbers and letters in parentheses indicate approximate impact on ENDF/B as follows: (1) very strong impact; (2) substantial impact; (3) weak impact; (R) data too recent to be included in evaluations; and (N) no ENDF evaluation at present.

†Isotopic data obtained.

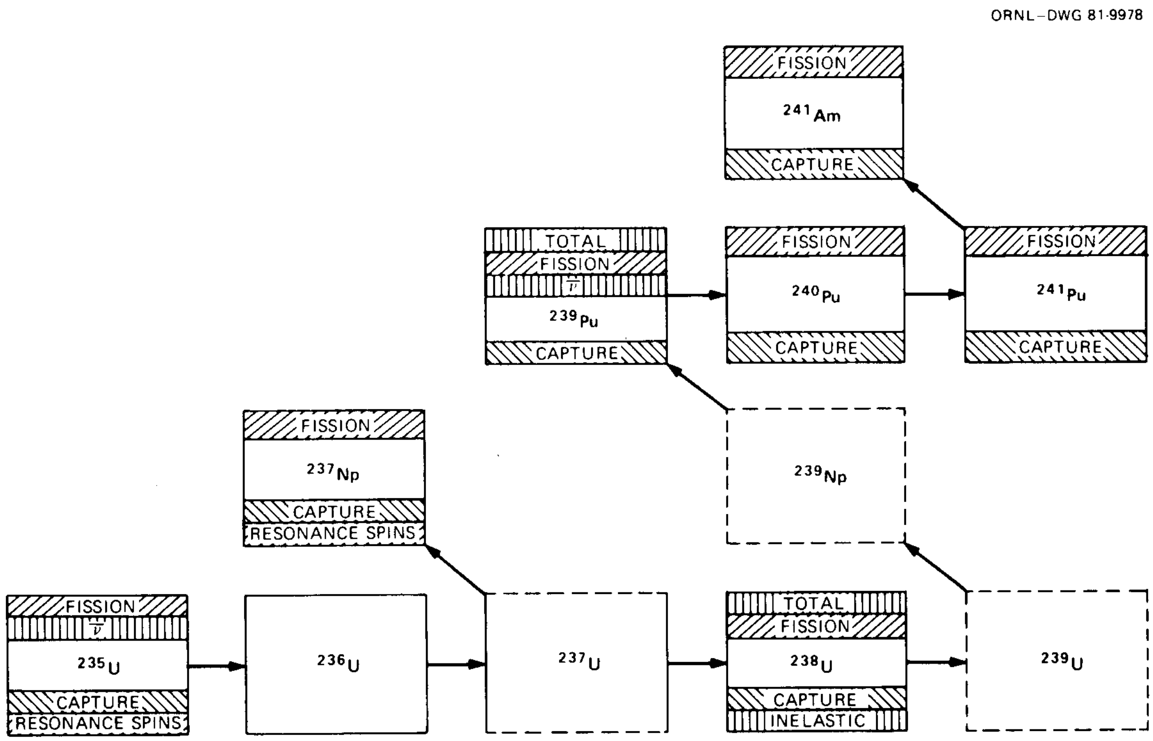


Fig. 2. Published ORELA Nuclear Data Measurements on the Fuel Nuclides of the U-Pu cycle.

region have been supplied, with only one material yet to be measured. These cross sections are necessary to predict heating in blanket regions and in superconducting coils, as well as radiation levels outside shields. The measurements performed are included in Table 2.

Other important fusion device data that are being obtained at ORELA are neutron emission spectra for 1- to 20-MeV neutrons incident on the materials of interest. These data have multiple uses. First, the neutron energies must be known in order to calculate the (radiation) damage inflicted when neutrons strike atoms of materials and displace the atoms from their normal lattice sites. Second, they are needed for the blanket and coil heating calculations, and, in addition, they are required for calculations of neutron breeding in blankets. To date, neutron emission spectra have been completed for five materials, with measurements for 10 additional materials planned.

Total cross-section measurements also have been made for fusion device programs, in particular to aid in the design of the Fusion Material Irradiation Test Facility (FMIT). It was discovered during the design of this device that for some materials the total cross-section data above 20 MeV were inadequate and for other materials they were nonexistent (Ca80). The situation was remedied with ORELA total cross-section measurements for 11 materials in the 2- to 80-MeV range meeting all the FMIT-related requests. These data are also useful in helping to determine the optical model parameters needed for calculation of *l*-dependent penetration factors.

A number of other measurements of interest for fusion device development have also been made. In particular, the $^{7}Li(n,n'\gamma)$ cross section for the 478-keV gamma ray and total cross sections for ^{6}Li and ^{7}Li in the 0.1- to 20-MeV region have been measured.

D. Defense Nuclear Agency Programs

Of vital interest to the Defense Nuclear Agency are nuclear data leading to the understanding of the transport of nuclear weapons radiation through the atmosphere and into structures. Thus, for nitrogen and oxygen and for the important constituents of soils and building materials, a variety of neutron-interaction cross sections are needed. At ORELA the emphasis for DNA has been on measurements of gamma rays produced in the various materials by neutron interactions. [These data are also of direct value to the fusion device program, because the neutron energy range is similar.] In addition, neutron total and scattering cross sections and charged-particle production cross sections have been measured for nitrogen.

DNA's need for the gamma-ray production data prompted the development of new techniques for these types of measurements, including the development of sodium iodide scintillators and lithium-drifted germanium detectors that are now being successfully applied in other programs.

E. ORELA's Impact on the National Nuclear Data Reference Set (ENDF/B)

ORELA data have impacted approximately 80% of the ENDF/B evaluations for the fissile and fertile nuclides and for structural materials. The known impact for specific cases is indicated in Tables 1 and 2.

In addition to providing the measurements, ORELA's staff keeps close contact with those responsible for maintaining the ENDF/B data sets. In fact, five ORELA staff members are themselves involved in ENDF evaluations (on a part-time basis) and three are co-chairmen of CSEWG committees. As a result, the staff is constantly aware of ENDF needs, and, conversely, CSEWG is kept informed on ORELA's measurement program.

How much improvement in nuclear data should yet be sought? This question is addressed in Section VI below. Here we note that the BES portion of the research was reviewed in June 1980 and again in June 1981 by DOE staff representing the fusion and fission application areas. They expressed explicit appreciation for the responsiveness of the bulk of the ORELA measurements to defined needs and suggested new work areas that could eliminate design uncertainties that still exist.

III. THE FIRST DECADE - BASIC NUCLEAR PHYSICS DATA

A. Introduction

Since ORELA began operation in 1970, basic nuclear physics data have been obtained for more than 150 different nuclides (from ^{1}H to ^{249}Cf) in the energy range from 10^{-2} to 10^{8} eV. Although neutron physics was already a mature field when ORELA came on line, the higher intensity neutron source and better energy resolution available at the facility, particularly in the keV energy region, made it possible to perform more highly detailed measurements, the analysis and interpretation of which have significantly increased our understanding of nuclear reaction mechanisms and of nuclear structure at high excitation.

In the energy window just above the neutron separation energy, neutron reaction experiments are unique in locating nuclear excited states and in determining the spins, parities, and decay modes of those states. Also, from an analysis of the detailed shapes of resonances and of the neutron cross sections between resonances, properties of the states outside the energy window under study can be estimated. The information gained through this window of accessibility is a crucial pinion that supports nuclear physics theory. Thus it is important to ensure that current nuclear physics theory is compatible with what is observed.

For a detailed study of a specific nuclide, the greatest possible variety of neutron cross-section measurements are made, including total, elastic differential scattering, inelastic scattering, and capture (including capture gamma-ray energy spectra). Many of the nuclides are studied because of their importance to understanding the s and r processes and the duration of stellar nucleosynthesis.

For these various measurements, new techniques, detectors, instrumentation, and data-acquisition programs have been developed and tested. Similarly, new techniques have been developed for analyzing the data, frequently involving the writing of computer programs needed to extract the basic nuclear physics information required for comparison with predictions from nuclear models.

Most of the basic nuclear physics data obtained at ORELA have been reported in detail at scientific meetings and in the open literature (see Appendix B). In the discussion below, we attempt only to point out some of the highlights of the research. We also wish to acknowledge that throughout this decade of measurements, ORELA's staff has frequently been strengthened by collaboration with visiting scientists from universities and laboratories throughout the U.S. and the world.

B. M1, E1, and E2 Giant Resonances in the Pb Isotopes

In a simple shell model picture, two 1^{+} states resulting from one-particle, one-hole configurations for neutrons and for protons are expected in ^{208}Pb at about 7 MeV, with the upper state at $\sim$7.5 MeV carrying most of the strength (Ve71). The interpretation of early photoneutron measurements from several laboratories indicated that about half the predicted M1 strength in ^{208}Pb, and also in ^{207}Pb, is located at excitation energies from 7.4 to 9.4 MeV (Bow70, To72, Ho77). However, the analysis of subsequent high-resolution neutron transmission and scattering measurements on ^{207}Pb at ORELA have shown that many of the states believed to be 1^+ states from these early photoneutron measurements were actually 1^- states, and hence transitions to the ground state were E1 transitions. Also, the d-wave contribution to many 1^- states (also populated by s-wave neutrons) was found to be quite strong. This was the first definitive observation of (s+d) admixtures.

Gamma-ray measurements with good neutron energy resolution were also made on ^{207}Pb at ORELA with several gamma-ray spectrometers in the excitation energy region from 7.4 to 8.0 MeV. The fine structure of the M1 strength in the 7.5-MeV excitation region (which contains ~20% of the predicted M1 strength) was obtained from these measurements. The major part of the M1 strength is probably located at a higher excitation energy. Improved experimental techniques, especially better resolution at high energies, are needed to identify such strength. The importance of locating the M1 strength for ^{208}Pb cannot be overestimated.

The analysis of high-resolution scattering and transmission measurements at ORELA on ^{206}Pb also showed that a large fraction of the states in the excitation energy region of ^{207}Pb from 6.7 to 7.4 MeV previously thought to have negative parity [and from early photoneutron measurements (Me74) to decay by M1 transitions to the $1/2^-$ ground state of ^{207}Pb] were excited by s- and d-wave neutrons and hence actually have even parity. The M1 strength in this energy region was less than 40% of that initially reported from photoneutron measurements. Again considerable M1 strength might be located at higher excitation energies and should be searched for when appropriate equipment is available.

As mentioned earlier, a large number of states observed in ^{208}Pb in the excitation energy region from 7.4 to 8.0 MeV are 1^- states and decay to the ground state by E1 transitions. It is well known that the E1 ground-state giant resonance lies at an excitation energy of 13.4 MeV in ^{208}Pb and has a width of 4.0 MeV. The measured E1 strength in the energy region from 7.4 to 8.0 MeV is 2.0% of the total, which is much greater than that expected from a Lorentzian shape for the E1 giant resonance.

From measurements at ORELA, 36 states in ^{208}Pb have been identified to be 2^+ and their E2 transition widths to the ground state have been measured. The measured E2 strength from 7.37 to 8.2 MeV accounts for 8% of the isoscalar strength. This strength is consistent with that expected from the tails of the E2 giant resonances at 11.0 and 8.9 MeV.

The high-resolution measurements at ORELA have been invaluable in assigning the multipole gamma-ray strengths in the Pb isotopes (Ra79).

C. Neutron Doorways, Valency Capture and Isospin Impurities

It is well known that the distributions of the neutron widths and level spacings for complex nuclides agree with the Porter-Thomas and Wigner distributions, respectively, and that long-range level spacing correlations agree with the theory of Dyson and Mehta; also, average properties such as the neutron and gamma-ray strengths vary smoothly with neutron energy and mass number. However, for light nuclides and nuclides near closed shells, nonstatistical phenomena are expected. The results from the high-resolution transmission and scattering measurements on ^{206}Pb, ^{207}Pb, and ^{208}Pb at ORELA have confirmed the previous observation (Fa65) of a doorway state in the s-wave channel for ~0.5-MeV neutrons for these nuclides. In addition, the ORELA data have given evidence for neutron doorways in the p- and d-wave channels. Doorway states in both the $p_{1/2}$ and $p_{3/2}$ channels for ^{206}Pb were found to be consistent with the observation of a doorway state for ~130-keV p-wave neutrons on ^{207}Pb forming 1^+ states. For the ^{206}Pb + n system, it was shown that the doorway states could occur from a $(d_{5/2},3^-)$ particle-core excitation. The d-wave doorway states which were observed probably arise from a recoupling of the $g_{9/2}$ neutron and the 4^+ core excitation which had been shown (Be70) to describe the doorway state in the s-wave channel. Localized concentrations of s-wave neutron strength observed for ^{54}Fe, ^{60}Ni, ^{66}Zn, and ^{68}Zn are also evidence of particle vibration doorway states at high excitation.

Nonstatistical effects were also observed in neutron capture cross-section measurements and from capture spectra measurements in several mass regions. For example, strong gamma-ray transitions measured at ORELA from p-wave resonances in ^{92}Mo and ^{98}Mo are among the most convincing examples of valence neutron capture. However, the neighboring nuclide ^{100}Mo did not shown any strong gamma rays from the p-wave resonances. This is most likely an example of an interference between the valency amplitude and another amplitude due to a narrow doorway rather than an accidental cancellation of valence and compound-nuclear amplitudes.

Significant correlations have been observed between the neutron and radiation widths for many resonances for several nuclides such as Bi, ^{28}Si, ^{90}Zr, etc. These correlations are evidence for the failure of the compound nucleus model for these nuclides, whereas such correlation is expected for valence capture.

High-resolution transmission and scattering measurements on ^{24}Mg at ORELA provided the first example using neutrons as the probe of isospin impurities in isobaric analog states. Although the $T=3/2$ isobaric analog states of the ground state and the first two excited states of ^{25}Na had been observed in charged-particle and photonuclear measurements, they had not been observed in neutron-induced reactions and their neutron widths were not known. The two neutron resonances which correspond to the first two $T=3/2$ analog states have neutron widths about 50 times smaller than the average of other d-wave $T=1/2$ resonances, indicating an isospin impurity of about 2%. However, a large s-wave resonance corresponding to the third analog state ($T=3/2$) has a reduced neutron width about 18% that of the average of three other $T=1/2$ s-wave resonances. Hence, it has an isospin impurity of about 18%. Results for other light nuclides are needed to further our understanding of isospin symmetry-breaking interactions of nuclear forces.

D. Angular Momentum Dependence of Optical Model Parameters

Except for light nuclides and possible closed-shell nuclides, the individual properties of the many levels found near the neutron separation energy are of interest only in the aggregate, because present nuclear models cannot describe these complicated states. Nevertheless, high-resolution neutron data are essential to determine not only the neutron strengths of the resonances for s-, p-, and d-wave neutrons in the energy region under investigation but also the contributions from resonances outside the region which are obtained from the potential scattering phases for the different partial waves. A technique using R-matrix analysis was developed for ^{32}S, ^{40}Ca, ^{60}Ni, and ^{206}Pb that produced not only the reduced neutron widths of resonances but also the contribution from resonances outside the region under investigation to the R function for each channel for s-, p-, and d-wave neutrons. Most earlier workers deduced only the neutron strength from the resonances inside the region and were not able to obtain information on the R function from outside resonances except for s-wave neutrons. The average strengths and R-functions depend on arbitrary boundary conditions; however, complex phase shifts derived from these averages are independent of the boundary conditions and therefore have physical significance.

The complex phase shifts obtained for s- and p-wave neutrons on ^{32}S, ^{40}Ca, and ^{206}Pb have been fitted with a spherical optical model in which both the real and imaginary well depths were allowed to be l- and J-dependent. The resulting real well depths for ^{40}Ca and ^{206}Pb showed no l-dependence, but those for ^{32}S did, being much deeper for p-wave neutrons than for s-wave neutrons (62 vs 54 MeV). The imaginary well depth for ^{32}S was smaller than that required to fit higher energy data, but showed no l-dependence. For ^{40}Ca and ^{206}Pb, however, the imaginary well depth showed an l-dependence. For ^{40}Ca the well depth is 10 times smaller than for s-wave neutrons, and for ^{206}Pb it is three times smaller than for s-wave neutrons. Information for more nuclides and comparisons to other nuclear models are needed.

E. Fission: Subthreshold, Threshold and Spin Determination

The first observation of intermediate structure in subthreshold fission for a few heavy nuclides and its explanation in terms of a double-humped fission barrier were reported in the late 1960's. From the strength, shapes, and spacings of the subthreshold fission clusters a great deal was learned about the properties of the first and second potential wells, such as barrier heights, differences between well depths, coupling between the states of the two wells, etc. During the past decade, high-resolution fission cross-section measurements have been made at ORELA upon ^{232}Th, ^{231}Pa, ^{234}U, ^{238}U, and ^{240}Pu to obtain details on these fission clusters and to increase our understanding of this phenomenon. For ^{240}Pu the height of the inner fission barrier was determined to be about 0.2 MeV higher that the height of the outer barrier, whereas for ^{234}U the outer barrier was about 0.5 MeV higher. Broad structures in the fission cross section of ^{234}U at higher energies were interpreted to be due to β-vibrational levels in the second well.

Angular distributions of the fission fragments from threshold fission were measured for ^{231}Pa and ^{232}Th. The data for ^{231}Pa were interpreted in terms of an asymmetrically deformed third well of the potential energy surface. Low-energy subthreshold fission and total cross-section measurements on ^{231}Pa at ORELA showed that the fission strength was randomly distributed over resonances and not in clusters. From the ORELA measurements it was concluded that the first minimum of the fission barrier was slightly lower than the neutron separation energy and the third minimum was rather shallow (0.5 to 1 MeV).

The most ambitious experiment carried out on ORELA in the first decade was the measurement, in collaboration with LANL, of the spins of the resonances in ^{237}Np and ^{235}U using polarized neutrons and polarized target nuclei. From both transmission and fission measurements on ^{237}Np, all nine members of the 40-eV group of subthreshold fission resonances were shown to have the same spin and to arise from a single level of spin 3 in the second well. All resonances in each higher energy cluster have the same spin, although the various clusters may have either spin 2 or 3. The measurements on ^{235}U determined the spins of more resonances in ^{235}U than had been determined by all other techniques in all previous years, and they also showed that assignments from other techniques were often wrong.

F. Gamma-Ray Spectroscopy from Neutron Resonance Capture

Neutron resonance capture gamma-ray spectroscopy is a valuable technique for studying the level schemes from the ground state of the compound nucleus up to an excitation energy of several MeV. Interference of unwanted gamma rays from low abundance isotopes is eliminated by selecting resonances in the isotope under investigation. Many nuclides have been investigated and level schemes have been developed placing primary as well as secondary gamma rays in the diagrams. For example, the energy levels of six odd tin isotopes have been obtained up to an excitation energy of 1.5 MeV. Various spectroscopic properties (level energies, electromagnetic moments, and transition rates) were calculated on the basis of a model which couples the odd neutron quasi particle to states of the even-mass core. The experimentally determined level properties were qualitatively reproduced by these calculations.

Level schemes were determined for several nuclides up to an excitation energy of ~4 MeV. The data for many nuclides show an unexpected decrease in the level density at an excitation energy of ~3 MeV. The explanation of this observation has yet to be developed.

The intensities of the primary E1 gamma transitions from resonance capture from ~10 nuclides have been compared to those expected from the width and position of the giant electric dipole resonance and the Axel-Brink hypothesis. After averaging over many resonances for a particular nuclide to compensate for Porter-Thomas fluctuations, good agreement was obtained with calculation. This analysis verified the Axel-Brink hypothesis, i.e., that a giant resonance built on an excited state should have the same energy dependence and strength as that built on the ground state.

G. Stellar Nucleosynthesis and Neutron Capture

During its first decade of operation, ORELA contributed a great deal of data relevant to the step-wise buildup of elements by neutron capture under conditions of temperature (kT ~30 keV) and density inside stars. When the process goes with explosive rapidity (r-process), it proceeds through neutron-rich nuclides up to those that spontaneously fission and the rates are determined by short beta decay lifetimes. When the process is very slow (s-process), as in deep layers of old red giant stars, the rates are determined by neutron capture cross sections of the stable nuclei for energies of ~30 keV, since most beta decay has time to occur between successive neutron captures. This process terminates by alpha decay just beyond bismuth. The ORELA neutron capture cross-section data on 105 pure or highly enriched isotopes in the mass range from 56 to 209 fit into the chain of theoretical s-process equations quantitatively. The predicted abundances of isotopes were in good agreement with the values found on the earth, on the moon and in meteorites. Where the r-process can also contribute to an observed abundance, ORELA measurements allowed that contribution to be singled out. This was particularly important in a few cases where a exceptionally long-lived decay step allowed the age of our galaxy to be inferred as 13.5 ± 2.0 billion years. A branch in the chain at A=204 allowed the s-process mean neutron capture interval (12-132 years) and neutron density to be calculated.

Even among the elements lighter than iron, for which charged-particle reaction networks dominate nucleosynthesis, neutron capture can have significant consequences. For instance, for the favored neutron source reaction $^{22}Ne(\alpha,n)^{25}Mg$ to drive the heavy element capture chain puts constraints on the competing reactions $^{22}Ne(n,\gamma)$ and $^{25}Mg(n,\gamma)$. In these reactions just one single resonance in the stellar temperature range can dominate the reaction rate and ORELA's high resolution becomes important.

IV. THE FIRST DECADE - CONDENSED MATTER RESEARCH

Since ORELA is a good source of high-energy (eV) neutrons that are provided in bursts with very small burst widths, the machine has possible uses for condensed matter physics for experiments that require good resolution and neutron energies high relative to thermal. The measurement of momentum densities is a good example of such an experiment, and trial experiments have been made on ^4He to look for Bose-Einstein condensation for temperatures below the λ point. Unfortunately, sufficiently good statistics could not be obtained to confirm the zero momentum state. If the ORELA performance were improved considerably, it would be very useful for this type of measurement.

Successful measurements were made on the hydrogen excitation energies of TiH and good agreement obtained with measurements made using reactors with hot moderator sources. Transmission cross-section measurements have been made on a number of materials to test them for use as neutron filters for reactor beams, and Si and Al_2O_3 are the best materials found so far. In doing these measurements, dips in the cross section have been noted that probably result from anharmonic phonon scattering. Analysis of these data is in progress. This type of measurement may be useful in determining the nature of the binding forces in materials.

V. FACILITY PERFORMANCE AND DEVELOPMENT, 1970 - 1980

A. Introduction

The utility of the ORELA facility in supporting experiments depends on its effective source intensity, its stability over single experimental runs up to 200 hours or more in length, its ability to produce the repetition rate and pulse width required by the principal experimenter, and its accommodation of simultaneous experiments. To these must be added the appropriateness and reliability of the detectors used in the experiments, as well as the data-acquisition and analysis apparatus. While some of these features were assured by the facility's original design, most require continuing tenacious effort by the staff. This section reviews some pertinent aspects of facility performance. [A recent description of ORELA has been given by Dabbs (Da80).]

A brief review of the ORELA technology will place this section in context. In a linear geometry, an injector places a short (4- to 50-ns) burst of 130-keV electrons into a four-section 1.3-GHz linac which uses stored rf energy to accelerate the electrons to ~140 MeV. The resulting beam of electrons usually strikes a small (0.06 liter) water-cooled tantalum target, inducing the production of photoneutrons whose total number is roughly proportional to the total energy in the electron pulse. A beryllium-clad water moderator surrounds the tantalum target on three sides.

Ten flight tubes diverge radically from the evacuated target room, and experimenters have access to the beams at ten stations along the flight tubes (see Fig. 1). A variety of pulse detectors, fashioned to be uniquely sensitive to a particular nuclear reaction of interest, allows measurement of the time between the electron pulse on the ORELA target and the detection of a particular neutron at a known "flight" distance -- that is, allows "time-of-flight (TOF)" measurements. By this means the cross section for a particular reaction can be determined as a function of neutron velocity or energy. Detector-dependent electronic apparatus, sometimes quite complex, is required to allow selection and timing of just those events associated with the nuclear reactions of interest. The logic-level outputs of the detector systems are fed to a common data-acquisition system in which are stored the arrays in which each element contains the number of events with equal flight time, detector pulse height, etc. Typically, 10^4 to 10^6 computer storage locations are required by each experiment. The raw data are subjected to a sequence of manipulations to reduce them to the required form for physics analysis.

In the accelerator itself, four 24-MW peak power (nominal) klystrons build up the stored energy in ORELA to about 120 J in the ~2.7-μs rf pulses applied to the accelerator waveguides; the rf generation system can drive the waveguide at any desired repetition rate up to 10^3 pps (Pe69). About half of a properly timed electron current pulse at the accelerator input will be accelerated. An electron pulse of a few nanocoulombs can be accelerated to about 180 MeV, but in pulses containing enough charge to deplete one-half the waveguide stored energy, the last electrons accelerated should reach only about 70 percent of the energy attained by the first. In practice, the energy spread is about 5 to 10 percent for small pulses but covers the whole range from 90 to 180 MeV for 50-J pulses. Since short pulses are desired to enhance resolution, performance of the injector is measured by the injected current, subject to the restriction that after-pulses and grid emission be avoided. Therefore, one hallmark of good operation is the amount of electron charge cleanly injected within the electron pulse width required by the experiment, and another is the amount of rf energy stored in the guide. Both directly affect the total electron energy deposited in the target and thereby the number of source neutrons per pulse.

B. Accelerator Performance

Table 3 shows the running-time breakdown of accelerator parameters chosen by principal experimenters during two typical years for which data have been compiled. In short-pulse operations the pulse width affects the experimental resolution and the exact value chosen is often a compromise to obtain sufficient intensity. For larger pulse widths the exact width often is unimportant (because moderator time spread dominates for neutron energies below $\sim$1 keV) and the experimenter's desire is for maximum number of neutrons per pulse.

Table 4 summarizes the machine availability and running time for several years. Prior to 1975, operation was scheduled for 12 (continuous) days in each two-week period, but since 1975 operation has been reduced to ten days out of 14 as an economy measure. Repairs following machine failures absorb only a small portion of the scheduled operating time, and scheduled shutdowns accommodate vacations and/or regular maintenance. Of the number of experimenters indicated in Table 4, some were tuning up equipment rather than obtaining final data, but such preliminary studies are of paramount importance to assure highest quality output in final runs.

Tables 3 and 4 relate primarily to ORELA reliability and productivity. The performance level is of prime concern also. For runs with maximum neutron production per pulse, the criterion would be energy (on the target) per pulse, while for shorter pulses the criterion should be energy per nanosecond of pulse width. (For operations at a 1000-pps repetition rate, a few percent reduction in output per pulse has always been observed.) Lewis (Le76) has reported broad pulses of about 65 J/pulse and narrow (5- to 10-ns) pulses of about 3 J/ns. Figure 3 illustrates the performance achieved over time; much of the time ORELA has not yielded the nominal output. (It should be noted that the experimenter may request reduced power, preferring to operate at reduced power rather than risk incurring a shutdown.)

Over the years the maintenance problems most responsible for reduced output have been:

a. inability of electron gun to "hold off" the design grid-anode potential,

b. electron gun inadequate or having a degraded cathode,

c. injector region vacuum poor ($\geqslant 10^{-5}$ Pa),

d. inadequate electron gun drive pulse (without inducing afterpulses),

e. klystron power low (usually cathode), and inadequate voltage holdoff in modulator (power drive for klystron) pulse-forming networks.

Of these, item d has systematically been the most serious problem since about 1979.

Table 3. Typical ORELA Operating Conditions*

	Year 1974				
Repetition Rate	3.5-5 ns	7.5-10 ns	24 ns	30-40 ns	Total
25 pps			8%, 1 kW		8%
200 pps		9%, 4 kW		2%, 10 kW	11%
300 pps		12%, 8 kW			12%
800 pps	14%, 13 kW	6%, 16 kW	5%, 25 kW	11%, 50 kW	36%
1000 pps	25%, 20 kW			8%, 60 kW	33%
Total	39%	27%	13%	21%	100%

	Year 1977			
Repetition Rate	3-6 ns	10-20 ns	30-45 ns	Total
25 pps			4%, 1.5 kW	4%
200-350 pps			12%, 20 kW	12%
600 pps			4%, 33 kW	4%
800-1000 pps	36%, 10 kW	8%, 25kW	36%, 55 kW	80%
Total	36%	8%	56%	100%

*For each repetition rate (in pps) and range of pulse widths (in ns), the table gives for the indicated year the percentage of the total beam time and the average beam power for that set of conditions. (As indicated in Fig. 3, the available beam power has been smaller in the most recent years.)

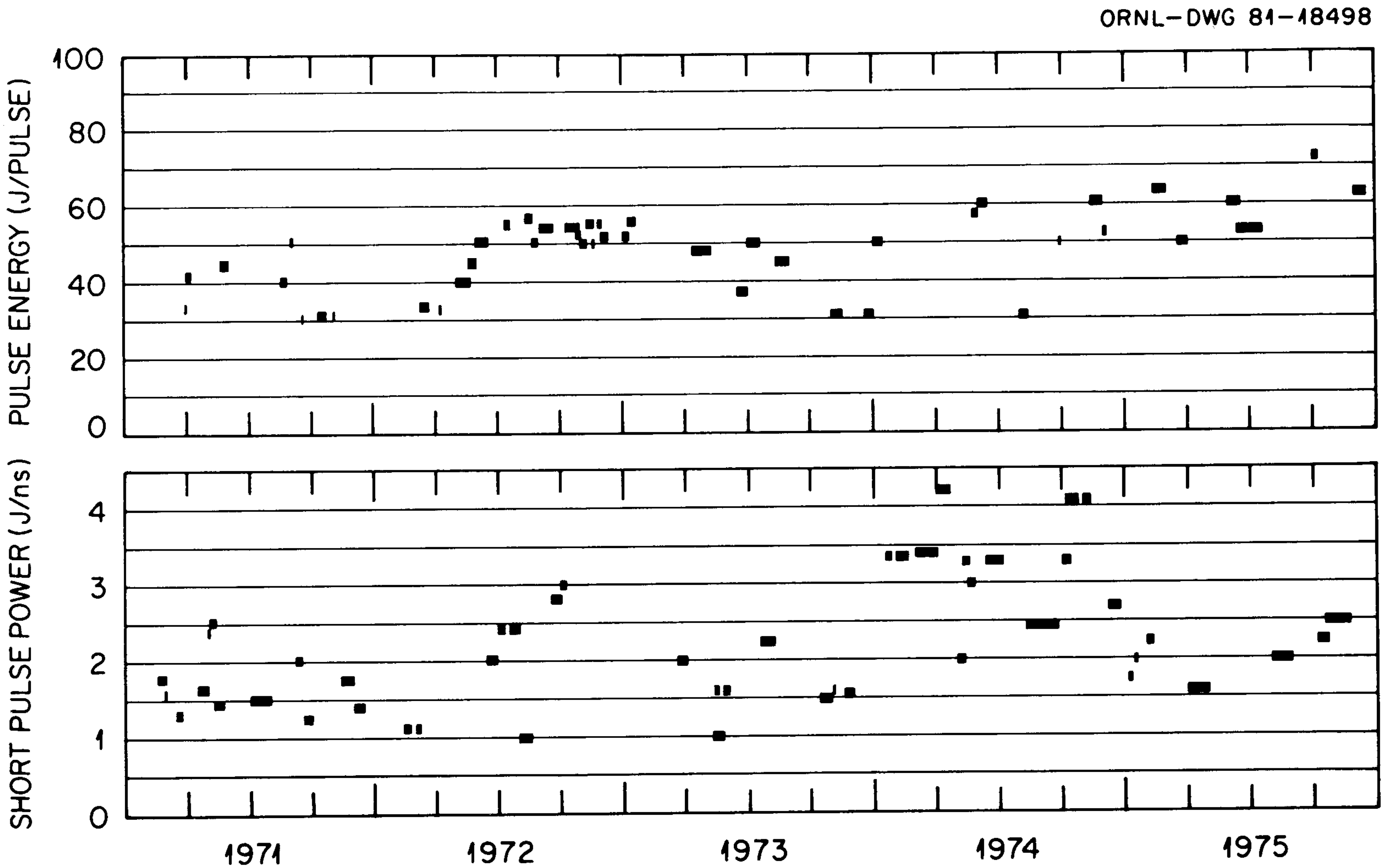
Table 4. ORELA Beam Availability

Year	Beam Hours	% Available[a]	Number of Experimenters[b]
1970	3693	71	4
1971	5538	90	4.4
1972	5203	88	3.7
1973	4547	89	4
1974	4797	87	4
1975[c]	5138	90	4
1976	4817	88	5.2
1977	4843	87	5
1978	3729	87	5
1979	5024	96	5
1980	3790	84	4
1981	4810	93	4

[a]Percentage of scheduled time for which the machine was available to experimenters.

[b]The average number of experimenters taking data at the same time.

[c]Reduced one operator in May 1975.


ORNL-DWG 81-18498
PULSE ENERGY (J/PULSE)
100
80
60
40
20
0
SHORT PULSE POWER (J/ns)
4
3
2
1
0
1971
1972
1973
1974
1975

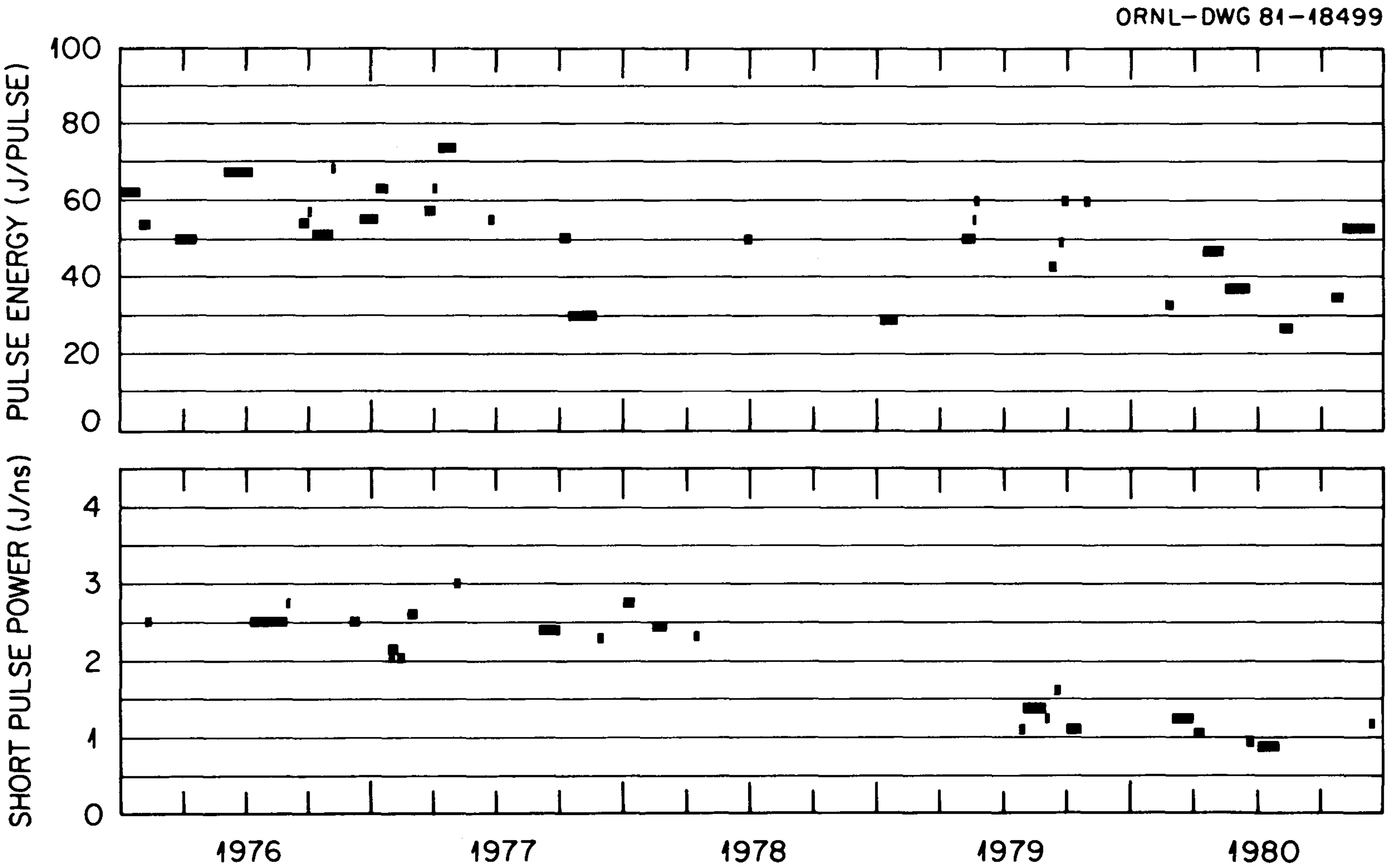


Fig. 3. Logged ORELA Output. The upper time series on each page shows recorded joules/pulse for runs with pulse width greater than 24 ns, while the lower chart in each case shows the recorded joules per nanosecond of pulse length for pulses 5 to 10 ns in width.

C. Accelerator Improvements

Maintenance of a machine like ORELA requires numerous and continuous efforts to improve machine components and subsystems that have proven troublesome. Some of the most significant improvements and their corresponding dates are as follows:

1. Redesigning and rebuilding "gun tank" that contains the electron injector systems operating at ~-150 kV (1972).
2. Redesigning electron gun ceramic to avoid voltage breakdown (1972).
3. Obtaining new-design oil capacitors and better rectifier and clipper diode components for modulators (pulsed 25-kV power supplies for the pulse-forming networks that drive the klystrons) (1972).
4. Redesigning accelerator time base and trigger generator (1973).
5. Installing a prebuncher system for injector (1976-82).
6. Improving SF_6 blower for microwave window cooling system (1981).
7. Installing hard-tube pulser for electron gun drive (1981-82).
8. Installing solid-state primary microwave source (1981).
9. Improving electron-gun grid designs to suppress grid emission (1980-82).

Installing the "prebuncher" (item 5) is a particularly complex and ambitious effort to enhance short-pulse neutron intensity by bunching the charge in a 15-ns pulse from the electron gun into a ~4- to 5-ns pulse at the wave guide entrance by slowing the early part of the pulse and accelerating the tail (ND74). Alsmiller *et al.* (A179) have projected the performance, but space charge effects will be so important that the calculations may not be fully reliable.* The design calls for specially shaped ~40-kV pulses to be applied to a series of nine ferrite-loaded accelerator gaps in such a way that ~15-ns rise or fall times are achieved. To date, the bunching achieved in tests is far less than the expected factor-of-four width compression, because vacuum problems caused by chloride stress corrosion have prevented a full test of the system. As of January 1982, a new set of gaps has been installed. Gaps of the modified design should not be subject to the corrosion problems of the original equipment.

In early years a staff of three engineers (plus operators) was associated with ORELA operation and development. In 1979-1981 the staff consisted of two engineers, an engineering technologist, and three operators. Four additional engineers have been associated with the experimental programs based at ORELA.

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*Very large energy changes must be applied to the electrons having original energies of ~130 keV. This is apparent from the fact that a 15-ns pulse at this energy is 2.7 m in length, while the whole prebuncher assembly is only 4 m.

D. Facility Improvements

Originally the ORELA facility had westward flight stations at 20, 30, and 40 m, and eastward flight stations at 10 and 80 m (see Fig. 1). Additional stations have been constructed on the west at 150 m and 85 m and from 40 to 60 m within a shield test station. On the east, stations at 200 and 35 m have been added. Basic beam line hardware is in use except on flight path 3, which is only partially equipped. The productivity of ORELA has been greatly aided by the variety of flight stations below ground level where they receive natural shielding against neutrons from other flight tubes. In most cases the collimation can be arranged so that the experiment "views" only the neutron source -- either the water moderator for slower neutrons or the tantalum target for fast neutrons.

The original aluminum-covered tantalum-water target yielded a neutron spectrum significantly affected by the resonances of aluminum at 6 keV, 35 keV, and above. Since 1974 the standard (tantalum) target has been encased in a beryllium can. An alternate target consisting of a beryllium block is sometimes used to emphasize production of high-energy neutrons (Bo70).

E. Detector Improvements

The intensity of ORELA has permitted use of high-performance* detectors having smaller overall counting rates per beam neutron than those required at earlier facilities. Below are listed the detector types used for various types of measurements at the facility. The detectors preceded by a dagger (†) were used primarily during the earliest years. Those preceded by a double dagger (‡) are widely applicable and becoming increasingly important. A significant amount of electronic equipment is associated with use of each of these detector systems.

Capture events
- †Large scintillator tank (3000-liter)
- Nonhydrogenous scintillator used as a "total-energy detector"

Neutron flux
- Liquid scintillator with pulse-shape discrimination (above 1 MeV)
- ‡NE-110 plastic scintillator (including use as "black" detector at low energy)
- ^{6}Li-loaded glass
- †Parallel-plate BF_3 ion chamber
- ‡Parallel-plate ion chamber with boron film
- Proton-recoil detector using hydrogenous film and silicon detector
- Xenon gas scintillation counter with ^{6}Li film

Neutron multiplicity
- 800-liter Gd-loaded scintillator tank

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*High performance in terms of time resolution and the ability to be sure of the energy dependence of detector efficiencies relative to the underlying cross sections.

Fission events

Thin-coated multiplate ion chambers (current mode)

Small spherical-shell segment or honeycomb ion chambers for high alpha-activity rejection

Secondary neutron spectrum

Liquid scintillator with PSD (pulse-shape discrimination between neutrons and gamma rays)

Secondary gamma-ray spectrum

12-cm-diameter NaI(Tl) scintillator

Liquid scintillator with PSD

Ge(Li) spectrometer

In most cases, detectors have been located in air (or sometimes in argon) at the end of evacuated flight tubes. However, evacuated scattering chambers have been found to be necessary for studies of scattered neutron angular distributions. The bibliography in Appendix B includes papers describing some of these detectors.

F. Data-Handling Systems

The linac time-of-flight facilities completed prior to ORELA quickly became "data bound" because they did not have adequate facilities to inspect and process the output of their experimental equipment. Therefore, from the beginning, considerable stress was placed at ORELA on assurance of efficient data-handling equipment.

The original data-acquisition system (Be69, Re70, Re77) consisted of two common computers (DACs) with specially organized disc storage units to permit sorting of data into 750 and 370 K categories or "channels." These storage areas can be divided on a rather flexible basis among four experimenters for each computer, and each computer can accept up to a total of 4- to 5-K events/second. Electrical isolation of the logic signals linking experiment output to these systems was given high priority to avoid ground loops that would adversely affect sensitive detector systems; experience has shown that large amounts of research time are wasted when such precautions against noise are omitted.

Improvements now in place include a third data-acquisition computer (DAC) that can store 5- to 6-K events/s into 10^6 channels, a separate computer to handle peripheral equipment and intercomputer links for the whole system, and modest extra memory (32-K words of 16 bits, total) for each computer unit.

The immediate analysis computer system, based on a PDP-10 with 200 megabytes of disk storage and four interactive graphic display stations for experimenters plus several standard terminals, was originally shared with the ORNL central computation system (Wi73). In 1976 the equipment was transferred to the ORELA building, and subsequent additions using equipment funds have brought that machine essentially to its full potential for our particular application. The tasks around which this machine was built involve the efficient graphic inspection of the large data sets required as successive corrections are applied to the data and as final results are compared to various models.

VI. FUTURE NUCLEAR DATA NEEDS FOR REACTOR PROGRAMS

A. Introduction

Nuclear data will continue to be needed in order for the many system parameters, involving neutron and fuel economics, radiation damage to structural materials, and the effectiveness of biological shields to be calculated with confidence. Specifically nuclear data are used to:

1. Define sources of secondary radiation (such as gamma rays produced when neutrons scatter inelastically, neutrons produced in fission, etc.).
2. Compute the disappearance of neutrons (such as through capture in fission products, in structural materials, etc.).
3. Account for the destruction/formation of nuclides through single or multistep nuclear processes (such as neutron captures that convert fertile nuclides to fissile nuclides, or reactions in fusion reactor structural materials that produce gases).
4. Calculate the transport of radiation through materials.
5. Estimate end effects on sensors, system components, and operations personnel (such as activation and tritium production cross sections, kerma, etc.).

Detailed data needs depend on the type of system being considered, the materials present, and the intended use of the results of their application. That is, if the data were to be applied to a feasibility study, the requirements would be less stringent than if they were to be applied to the design of an operable (but not necessarily optimized) device. Similarly, the requirements would be even more stringent if they were to be used to design a system (e.g., a reactor) whose cost and fuel efficiency must be optimized.

In the following discussions of the needs for new nuclear data for application to various reactor systems, it is to be remembered that new measurements become useful to designers or system analysts only after a data evaluator has combined the new information on a particular material with the data already available on that material and has represented the result in a carefully formatted cross-section file such as the official U.S. reference set (ENDF/B). Needs for new data should in principle be established on the basis of benefit-cost analyses. However, needs so defined cannot always be addressed directly because progress toward a sufficiently accurate data base depends in part on the development of cross-section systematics, nuclear theory, and cross-section and other nuclear standards.

It is worth noting the time scale required to accumulate a large body of data such as that described in Section II. Nuclear-data measurements and evaluations are time-consuming processes, especially if the improved accuracies required for the design of economically interesting power plants are to be met. Also, time must be allowed for the interplay and cooperation required among workers using contrasting facilities and techniques.

Occasionally, needs for new data can be met quickly, as was the case for the high-energy total cross sections required for FMIT design (see Section II-B). However, this possibility depends upon the existence of an established experiment facility. Thus, as with similar programs in other areas, it is cost effective to continue a rather stable experimental effort. Attempts to suddenly increase efforts in order to obtain data quickly are usually expensive. At the other extreme, allowing facilities to cease operation when they will be required later is probably the most expensive approach of all. An intermediate level of continuous effort with only gradual changes is surely fiscally optimum considering the variety of programs that depend upon nuclear data.

B. Formal Definition of Nuclear Data Needs

There exists in the U.S. a considerable infrastructure for determining nuclear data needs and attempting to meet them [CSEWG and DOENDC (Department of Energy Nuclear Data Committee), plus *ad-hoc* advisory groups for reactor physics and other areas]. The groups are largely government funded, and requests for specific nuclear data are largely from government programs (primarily from DOE programs), although some are also received from private organizations, for example, certain private medical facilities. A rather complete formal compilation of requests for nuclear data measurements is maintained by the National Nuclear Data Center (NNDC) with the aid of CSEWG. This compilation was last issued in March 1981 (ND81).

Once important nuclear data have been measured, they must be experimentally confirmed by other (independent) measurements. The substantial cost of experiments makes international cooperation imperative. The "World Request List for Nuclear Data," an integrated statement of nuclear data needs for the world prepared by the IAEA in Vienna, was last updated in May 1981 (IA81). Generally, the data requests from the various countries are consistent, although the different approaches to data adjustment are reflected in the stated needs.

The various compilations for nuclear data requirements attempt to cover all relevant programs, but it is not possible to set priorities or accuracy requirements on a completely consistent basis. For the mature fields such as fission-reactor design, the perceived needs reflect either much accumulated experience in the design process or, less commonly, the application of modern sensitivity and uncertainty analysis. Formal and credible benefit-cost studies are not available, and even if they were, they would depend on poorly known parameters of our energy future. The paragraphs below reflect briefly the needs of the various U.S. programs for additional experimental data on neutron interactions.

C. Light-Water Reactors

While light-water reactors can be designed with existing nuclear data, a case can be made for the cost effectiveness of improving these data. Ryskamp, Harris, and Becker of RPI (Ry81) show large uncertainties in nuclear fuel-cycle costs due to uncertainties in nuclear data [approximately one-half million (1985) dollars for one core loading and one cross section*]. The largest single uncertainty was found to be associated with the ^{239}Pu

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*This reference may suggest too much potential benefit in that information from operating experience is apparently not included and in that data uncertainty can never be null. Operating data, however, are inherently incomplete.

(n,γ) reaction. Based on this study, the needed meticulous measurements could be made with existing major equipment at ORELA at costs which could allow *positive payback for one reactor core*! An important argument for such measurements is that calculational capabilities are being improved and more and more being adopted by utilities, so that data of higher accuracy will be used.

Future LWR data needs include more precise nuclear data for higher-A isotopes. These isotopes will increasingly be built up in the longer-lived cores now being contemplated and thus they will have to be considered when designing for increased fuel efficiencies. Because of the long lead time required to schedule the measurements, analyze the data, and perform new evaluations, the effort should be initiated now.

For commercial power plants, the accuracies in design which are achieved and are justified by cost reductions are closely guarded -- i.e., they constitute proprietary data. Nevertheless, over the years, a number of potentially useful summaries of such information have been presented, mostly in specialists' conferences. Review of these data is beyond the scope of this document but may be found in a forthcoming report by Weisbin *et al.* (We82). Recent conference presentations by Weston (We79) and by Ozer (Oz80) also have covered the LWR data needs.

D. Fast Breeder Reactors

Providing nuclear data for fast breeder reactor design has been a very difficult task that has received much attention. Most data problems for U-Pu cycle FBRs have been attacked and some of the relevant data may now be known well enough to support a commercial FBR industry.

According to LeSage (Le80), uncertainties in basic nuclear data continue to be the largest cause of uncertainties in predictions of the physical performance of FBR systems. (Those who prefer to rely most heavily on "engineering mockup" integral experiments might disagree.) LeSage points out problems with neutron capture cross sections, difficulties in studying inelastic scattering for fissile materials (resulting in poorly known cross sections), and an uneven quality of data for the resonance region and for fission-product cross sections. Above all else, LeSage emphasizes the importance of increased accuracy for standards, especially for the ^{235}U(n,f) reaction and for ^{252}Cf($\bar{\nu}$).

Neutron capture in ^{238}U remains intractable in the sense that differential measurements still seem to imply spectrum-averaged values for some critical assemblies that differ from experiment. Fission and capture for ^{239}Pu, and capture in stainless steel, are identified by Lineberry *et al.* as needing more accurate measurements (Li81). Hammer (Ha80) and Rolands (Ro78) have recently summarized FBR data needs.

Past assessments of nuclear-data needs for FBRs have tended to emphasize feasibility questions rather than to stress cost impacts. Feasibility and short-term safety are much less in doubt since FBRs are now operating in several countries and the controlling question is "What will be the cost of electricity from commercial-size power plants?" Future data needs for FBRs must be examined in this context and this process has scarcely been started in the United States. Even though sensitivity and uncertainty analysis are far advanced for reactor-physics studies, their contribution to cost/benefit tradeoffs for future research, including nuclear data measurements and evaluations, is largely yet to be demonstrated. The paper of Weisbin *et al.* (We82) is expected to provide a review of progress in this field.

For commercial-size LMFBRs, the shields tend to become so massive that seismic design problems become more significant. Reductions in shield weight are possible with more expensive boron-containing materials and use of the materials appears to be cost effective. The relevant cross sections must, of course, be precisely determined.

An area not yet well addressed in the U.S. is the direct measurement of self-shielded cross sections. This point was forcefully made by L. N. Usachev in (unpublished) remarks at the 1979 Knoxville (Tennessee) Conference on Nuclear Cross Sections for Technology. He stated that measurement of capture cross sections (below 20-50 keV) for infinitely dilute ^{238}U is barely relevant to practical breeder reactors, and moreover that energy-dependent self-shielded cross sections in the flat-background Bondarenko approximation can be obtained directly from appropriate experimental data. Changes in self shielding from the Doppler effect play a particularly sensitive role in the temperature coefficient. Some work of this type has been performed (Ba80).

ORELA's greatest contribution to the FBR program perhaps will continue to be in the area of capture cross sections. New techniques for measuring capture-to-fission ratios, claimed to be good to 2% in favorable cases but not yet tested at ORELA, may permit accurate measurements of the capture cross sections of fissile materials (Mu80). In a close "second" should be the narrow resolution ORELA studies of the resonance structures of reactor materials.

E. High-Temperature Gas-Cooled Reactors

HTGRs are now studied in three countries because of their unique potential as nonpolluting heat sources for industrial processes (production of oil from tar sands or oil shale, for example). They can also conserve water in electricity production because they permit the use of dry cooling towers while retaining good thermal efficiency. HTGRs effectively utilize thorium as an energy source (indirectly via conversion to ^{233}U), and nuclear data are needed for evaluation of proposed designs. While the data base for ^{233}U and ^{232}Th has been much improved in the past few years owing to studies in NASAP (Nonproliferation Alternative Systems Assessment Program), a serious HTGR development push would motivate additional work to assure correct calculation of the temperature coefficient, conversion ratio, and perhaps the production rates of difficult-to-handle isotopes.

F. Fission Reactor Fuel Cycle and Waste Disposal Programs

Neutron cross sections that can be used to determine the composition and thereby the hazards of the actinide component in the spent fuel waste stream are badly needed. A thorough international effort in the last seven years to survey and solve this "transactinide" cross-section problem (Ia75) has included a significant effort at ORELA. It is presently believed that the main cross-section measurement needs in this area will have been met when current work is completed (a "victory"), though a significant amount of evaluation work remains.* As existing data are further digested and used, some needs for improved accuracy are likely to be identified; in the U.S. this will be more likely when fuel reprocessing and waste storage are undertaken and especially if plutonium is recycled.

*For a contrary view with respect to (n,2n) and (n,γ) reactions, see Bobkov (Bo79).

G. Fusion Test Facilities and Reactors

The higher energy of the primary neutron source in fusion reactors using D-T fuel (14 MeV) has required extending the energy range of nuclear data measurements and evaluations above that of interest in fission reactors. Also, additional reactions become important, e.g., activation reactions and reactions that produce charged particles which in turn form gas inclusions (microbubbles) within structural materials.

Shields, blankets, and structural components for fusion reactors are remarkably complex with many penetrations, and some materials will be used for which cross sections have not been studied very extensively in the past. For example, tungsten must be considered as a shield for particularly difficult regions. Also, for the more complex reactions taking place [e.g., the (n,n′p) reaction], different nuclear theories must be considered and additional information (such as strongly asymmetric angular distributions) must be obtained.

The dominant fusion device neutron measurement needs are for nuclear recoil spectra, transmutation data, and gas-production cross sections to estimate materials damage; differential neutron scattering cross sections for neutron transport calculations; and dosimetry cross sections to permit accurate flux monitoring in test facilities. A particular need is for precise ^{7}Li(n,n′α)T cross sections to estimate tritium breeding performance.

Designing the test facilities themselves requires new nuclear data. For example, radiation damage so dominates fusion-reactor design that extensive engineering studies are required. But providing sufficiently intense neutron sources with suitable energy spectra for such test facilities is inordinately difficult. The planned use of a deuteron-on-lithium neutron source has required the determination of neutron cross sections up to ~50 MeV for the facility design (Ca80). Interpretation of the irradiation results from this or other facilities will depend largely upon analysis of induced activities. The cross sections for the relevant reactions over the extended energy range must be carefully determined. The energy range at ORELA is appropriate and can be further optimized. However, ORELA is not useful for direct measurement of differential activation cross sections.

The use of continuous-energy (white) neutron sources such as ORELA for measurements of secondary charged-particle spectra is a new approach and has been demonstrated only partially. This remains a most active area of investigation.

A summary of all recognized U.S. needs for the Magnetic Fusion Energy Program was provided to the Department of Energy Nuclear Data Committee by the Office of Magnetic Fusion Energy in April 1980 (Ng80).

H. Hybrids and Other Systems

Interest arises from time to time in alternative power systems such as fission-fusion hybrids, electronuclear fuel production with high-energy accelerators, and different types of reactors such as the BNL mixed-spectrum reactor proposal. It is prudent to maintain a complete general-purpose nuclear-data base which allows scoping evaluations of such systems without major errors due to missing or obsolete nuclear data. This became quite apparent in the NASAP studies of a few years ago when alternative breeder performance estimates contained large uncertainties due to the ancient nature of the nuclear data for thorium.

I. Plutonium Production Reactors

The production of plutonium and other special materials continues for the nation's weapons program. The existing facilities are limited in capability and are aging. There have been recent indications of a need to both replace and expand plutonium-producing reactors. The choice of reactor type for this replacement is yet to be made. However, due to the clear emphasis on neutron economy and the overall cost of the system, it will surely be advantageous to provide more precise nuclear data for the design of the replacement. With its wide energy range, ORELA would probably be the best provider of these data.

J. Comments on Determination of Measurement Needs

Qualitative data needs for a particular program area can usually be determined by considering the current state of data for the materials and energy regions where reactions occur in the devices being considered. When a system has been so thoroughly analyzed that the important cross-section behaviors are recognized (e.g., the resonance cross-section minimum in ^{23}Na for LMFBR systems), quantitative sensitivity/uncertainty analyses can be performed to indicate priority cross-section studies. If cost/accuracy of such experiments could be predicted, priorities could be rather precisely ordered (We82). Experiment costs depend crucially upon the availability of suitable neutron sources, detectors, and staff, so that novel rather than incremental data measurements usually require both considerable time and funding. Thus cost figures are hard to estimate, correlations among results from future experiments are usually obscure, and the derived priorities depend on current system-performance parameters which are likely to change. Further, the priorities depend globally on the way in which results from integral experiments are combined with the differential data. Consequently, sensitivity/uncertainty results are presently best taken as semiquantitative indications of priority that can supplement and refine qualitative findings.

As advanced energy systems such as Fast Breeder Reactors or Fusion Energy Reactors approach the stage of commercial operation, requirements for design accuracies will become much more stringent. Such accuracy in design must be based upon the results observed in the operation of demonstration plants, upon integral experiments, or upon differential data, including nuclear data. Past experience and reasonable extrapolations thereof indicate strongly that all three of these areas must contribute in order to provide economically viable designs of new power systems. This conclusion, plus the relatively modest cost of incremental nuclear-data measurements imbedded in a continuing program versus the much larger costs of spasmodic measurement, argue strongly for a steady nuclear-data measurement and evaluation program.

VII. FUTURE BASIC NUCLEAR PHYSICS GOALS

A. Introduction

The goal of the basic nuclear physics program at ORELA is to increase our understanding of the atomic nucleus through studies of fundamental neutron-nucleus interactions. Measurements of neutron reactions with nuclei and their subsequent interpretations have contributed greatly to the development and testing of nuclear models for complex nuclides and will continue to provide input for new concepts in nuclear physics.

Neutron reactions will continue to be valuable probes for nuclear structure studies to excitation energies as high as ~10 MeV or more for many nuclides. The structures of many nuclides have been thoroughly studied up to a few MeV of excitation and many features are now understood. However, more data are needed at higher excitation energies in conjunction with further theoretical developments.

For an energy window ~1 MeV wide just above the neutron separation energy (~5 to 11 MeV, depending on the nuclide), high-resolution neutron spectrometry will remain the essentially unique technique for locating and measuring the properties of highly excited states. The spins, parities and principal decay modes of these nuclear states can be obtained. In the next decade, measurements at ORELA should be able to widen this energy window to 2 or 3 MeV for many nuclides. Neutron and gamma-ray strengths averaged over this energy window will be compared with predictions of optical and giant resonance models of the nucleus. Concentrations of the neutron, gamma-ray or fission strength for particular values of spin and parity over relatively small energy regions will be searched for and interpreted by means of more detailed nuclear models. Such concentrations would be evidence for "simple" modes of excitation such as fragments of single-particle excitations, particle-core excitations, quasi-particle excitations, etc. The observation of particle-core excitations in this energy region would strongly support the concept that these types of excitations contribute to the spreading width of giant resonances observed at higher energies using other probes.

Neutron-capture gamma-ray spectrometry will continue to be a fruitful technique for determining the location and properties of states for selected nuclides up to ~4 MeV excitation. There is an intriguing indication of an abrupt change in nuclear level density at an excitation energy of a few MeV for several medium and heavy nuclides. This effect is suggestive of a breaking of nucleon pairs in the nucleus and warrants detailed study. Unusual gamma-ray strength to selected low-lying excited states will be searched for and considered in terms of simple configurations of the initial or final states. Such simple configurations are to be expected from Wigner's supermultiplet theory.

Neutron spectroscopy also has some interesting implications in other fields of nuclear physics. For example, the neutron resonance structures of ^{86}Kr+n and ^{136}Xe+n are needed to interpret and evaluate the neutron spectra following β^- emission to highly excited states of ^{87}Kr and ^{137}Xe. These are the only two neutron emitters produced by β decay of fission products which are also accessible by neutron spectroscopy. ^{86}Kr+n has been studied at ORELA and ^{136}Xe+n will be investigated. The distribution of partial β decay widths of ^{87}Rb and ^{137}I obtained from the analyses of the delayed neutron spectra will be a sensitive test of the dependence of β branching on nuclear structure.

Detailed analysis of the high-resolution data will be carried out to search for results indicating the failure of concepts of the nuclear models now used to explain nuclear phenomena at high excitation. Increasing interaction with nuclear theorists through workshops and collaboration will consolidate the significance of the conclusions and stimulate future research with neutrons. Additional techniques and equipment will need to be developed to pursue new types of experiments not presently emphasized at ORELA.

Additional plans are outlined in the following sections and the types of measurements and program needed to accomplish these goals are discussed.

B. Total and Scattering Cross Sections

Neutron total and scattering cross sections of many light nuclides and nuclides near closed shells will be studied for neutron energies up to several MeV. Examples of these are ^{20}Ne, ^{28}Si, ^{40}Ca, ^{48}Ca, ^{48}Ti, ^{52}Cr, ^{56}Fe, ^{58}Ni, ^{88}Sr, ^{90}Zr, ^{204}Pb, ^{207}Pb, and ^{208}Pb. Not only will the neutron widths of the excited states produced by s-, p-, d-, and possibly f-wave neutrons be determined, but potential scattering phase shifts for the various l-values will be obtained. Techniques will be developed to interpret the neutron strengths obtained from the resonances in the region being studied, as well as the contributions of resonances outside the region. Complex phase shifts for various l-values will be determined from these data for comparison with predictions from nuclear optical models. The real and imaginary well depths for a spherical nuclear optical model required to fit the data will be deduced in order to search for additional evidence of a possible l-dependence of the well depths (indicated by measurements at ORELA for a few nuclides) and for a possible systematic dependence upon mass number and nuclear deformation.

A search will be made for local concentrations of the d-wave strength in ^{207}Pb+n (a prediction from shell model calculations for neutron energies of 2.0 to 2.5 MeV) and also in other nuclides in this mass region. If f-wave neutron strength is found in ^{40}Ca+n in the unbound region, a subsequent experiment should be performed to search for M1 radiation to the ground state. Measurements will be made on ^{204}Pb to investigate the effects of fragmentation of the particle states on the spreading widths of particle-core doorway states observed in other Pb isotopes.

Isobaric analog states in light nuclides will be sought, since their neutron widths are measures of the isospin impurities of the states. Isospin impurities arise from the Coulomb interaction and from a charge-dependent nucleon-nucleon interaction. Other experiments, such as β decay, have shown that isospin is a good quantum number, and that isospin impurities when present are extremely small (<<0.1%). Earlier ORELA measurements indicated much larger isospin impurities for ^{25}Mg, as high as 18%. Observation of such large impurities are important, since they are much greater than theoretical estimates based on simple models. Additional examples of isobaric analog states with large isospin impurities are needed.

C. Capture Gamma-Ray Spectra

Neutron-capture gamma-ray spectra measurements from individual resonances will continue to contribute to the understanding of the tail on the low-energy side of the E1 giant dipole resonance for medium-weight and heavy nuclides. Previous measurements on ^{207}Pb, which unravelled the microstructure present in the tail (7.4- to 8.2-MeV excitation) of the isoscalar giant quadrupole resonance, will be extended to ~11-MeV excitation. The dependence of the partial radiation widths of individual resonances (and the gamma-ray strengths averaged over resonances) upon the spins of the resonances will be determined for the nuclide ^{171}Yb and other nuclides in this region.

Several nuclides near closed shells will be studied with low-energy neutrons to look for additional evidence of nonstatistical effects (i.e., departure from compound nucleus formation) such as valence and direct capture, etc. Valence capture and direct capture can be identified by the strengths of the gamma transitions to discrete final states, from correlations with (d,p) spectroscopic factors, and correlations between neutron widths and partial radiation widths of individual resonances. Careful analyses of the gamma-ray spectra of these medium and heavy nuclides will provide level structure information up to several MeV excitation, which often cannot be obtained by other techniques. Gamma-ray strengths of light nuclides from the capture of MeV neutrons will require the development of a new efficient gamma-ray detector located at a long flight path. For gamma rays to discrete final states, microscopic models predict angular distributions that are very sensitive to the different components of the nuclear reaction process and shell model structure of the final state. Recent results indicate that macroscopic models based on direct plus semi-direct processes are unable to reproduce these angular distributions, and such data would be stringent tests of microscopic models. Measurements of the capture of MeV neutrons will provide data relating to the need for velocity-dependent potentials, for the role of the effective nucleon mass, and for the coupling to the Δ meson resonance.

D. Capture Cross Sections and Nucleosynthesis

Although neutron-capture cross-section data have been obtained on ~150 nuclides, techniques have recently been developed to use isotopic gas samples and to extend the data to several MeV neutron energy. At the higher neutron energies, direct and semi-direct capture become the dominant modes of radiative capture, while statistical or compound nucleus capture is small. However, the macroscopic models used so far in the 1- to 10-MeV energy range have shown important deficiencies in cross-section predictions, and microscopic models seem necessary to reproduce both the gross behavior of the cross section and its fine structure components. Capture cross-section measurements are particularly sensitive for detecting resonances with very small neutron widths, which are often not found in transmission measurements when only small samples are available. The detection of almost all these small resonances is essential for determining the level density of states of the same spin and parity. Effort will be devoted to a verification of the prediction of a parity dependence of level density for states of the same spin in several mass regions. Correlations between neutron widths and total radiation widths of resonances will also be investigated for several nuclides; such correlations are evidence for external neutron capture rather than compound nucleus formation.

The buildup of the elements beyond iron by successive neutron captures tens of years apart inside stars (the s-process) is quantitatively determined by stable isotope neutron-capture cross sections near 30 keV. ORELA data have helped confirm this picture for average solar system material and allow the calculation of the supernova (r-process) component for those isotopes made by both processes. At a few places in the periodic table the s-process shows a branch because of a particularly long beta decay lifetime. Detailed studies (Re-Os, Lu etc.) at these branch points yield information on the age of the galaxy and/or the interior stellar temperatures at nucleosynthesis sites. Some of the rarest isotopes and abundance anomalies found in certain primitive meteorite inclusions have sparked renewed interest in an intermediate element building process (nβ) probably connected with the initiation of solar condensation from interstellar gas. This is pointing up the need for capture cross-section measurements on some of the neutron-rich isotopes just off the line of maximum beta stability. Specific nuclides which are also important to nucleosynthesis, such as ^{22}Ne and isotopes of Hf, will be studied.

E. Inelastic Scattering Cross Sections

The technique using an iron-filtered neutron beam will be pursued for measuring neutron inelastic scattering for the energy regions just above the thresholds for the first several excited states of heavy nuclides, such as ^{232}Th. Also, effort will be made to obtain neutron inelastic scattering widths of resonances for incident neutron energies just above the threshold of the excited state from both the pulse height and the time of flight of the neutrons scattered by resonances. The behavior of the inelastic strength, such as a local concentration and dependence on the spin and parity of the compound state, will lead to a determination of the configuration of the state. The yield of gamma rays from the 2^+ state of several even-even nuclides, such as ^{56}Fe and ^{28}Si, will be measured up to ~20-MeV neutron energy and interpreted in terms of present nuclear theories. A measurement of the ^{187}Os(n,n′) cross section to the first excited state at 9 keV will be attempted on ORELA by use of an original technique involving the use of the 23.4-keV neutron window in a laminated iron and aluminum filter placed in the scattered neutron beam. This inelastic cross section is of special interest for the "^{187}Re-Os clock" for determining the age of the universe.

F. Fission Cross Sections

Studies of the angular distribution of fission fragments in the threshold region from ~0.3 to 2 MeV for several nuclides will be made; a few of these will be in collaboration with LANL and others. For these measurements a suitable, efficient detector and associated equipment will need to be developed. The addition of pulse-height information needed for the angular distribution studies will also improve the quality of fission cross-section measurements. Angular distribution measurements on nuclides such as ^{230}Th will give information on nuclear deformation, K-band structure, and data relating to the triple-humped barrier interpretation.

G. Other Cross Sections

Equipment and techniques will be investigated to measure (n,α) and (n,p) cross sections for a few special nuclides in the rare earth region and around mass number 60 which have relatively high positive Q-values for these reactions. Alpha and proton widths of the low-energy resonances will be derived from the measurements. Distributions of the alpha and proton widths will show whether the reactions are single exit channel processes such as elastic neutron emission, or multichannel such as neutron capture, or few-channel processes such as fission. If a sufficiently wide energy region can be examined, nonstatistical effects might be observed, indicating the importance of nuclear deformation and nuclear structure on these reactions.

VIII. RELATIONSHIP OF ORELA TO OTHER PULSED-NEUTRON FACILITIES

Only those facilities with "white" pulsed-neutron sources of moderated and unmoderated Maxwellian neutrons produced from particle accelerator beams enable neutron time-of-flight measurements to be performed over an energy range that extends from thermal energy up to the energies needed for fusion reactor studies. For measurements above a few eV, accelerator sources have proven to be superior to reactor sources. Monoenergetic pulsed sources, which are limited to energies above at least 100 keV, have tended to complement "white" sources.

During most of its first decade of operation, ORELA (Pe69) has been substantially superior to other "white" sources used for neutron TOF measurements. This commanding position has been reduced, however, with the upgrading of the CBNM electron linac at Geel (GELINA) (Be81), the construction of the Harwell electron linac (HELIOS) (Co77, Ly80), and the addition of the Weapons Neutron Research Facility (WNR) (Au80, Ru77) to LAMPF. Moreover, the Proton Storage Ring (Law80) funded for LAMPF has the potential to be much more intense than the ORELA neutron source. These facilities, together with the KFK sector-focussed cyclotron useful above 0.5 MeV (Ci78), the IBR2-LIU30 pulsed-reactor and accelerator complex at JINR (Lu80), and electron linacs at NBS, LLNL, RPI, and JAERI will all be used as "white" neutron sources for neutron cross-section TOF measurements.

Table 5 compares ORELA's maximum neutron production per pulse and per second, at the maximum pulse rate, to those of its probable major near-term competitors: HELIOS, GELINA, WNR, and PSR. The other electron linacs are generally less intense than ORELA. Comparisons are made for both short- and long-pulse modes used for MeV-keV and meV-eV TOF measurements, respectively. With the prebuncher,* ORELA should be capable of producing 8×10^{10} neutrons in a 4-ns pulse, giving 8×10^{13} neutrons/s at ORELA's maximum 1000-pps rate. This prebuncher is expected to increase the short-pulse intensity by nearly a factor of three. A full 40-ns-wide ORELA pulse produces 13×10^{10} neutrons, giving 13×10^{13} neutrons/s at 1000 pps; however, this maximum pulse rate is rarely used for eV-range measurements because of time-frame overlap.

HELIOS is an L-band electron linac that is very similar to ORELA and has an unloaded beam energy of 136 MeV. Its design rf power levels and accelerated-electron currents are smaller than those achieved with ORELA; however, planned use of a ^{238}U neutron-producing target will allow intensities nearly equivalent to those from ORELA without the prebuncher. (At the expense of increased complexity, backgrounds, and safety concerns, a ^{238}U target can increase the neutron production by a factor of two over the tantalum target used by ORELA.) HELIOS has long-pulse modes in addition to those shown in Table 5.

GELINA is an s-band electron linac with an unloaded beam energy of 150 MeV; it also uses a ^{238}U target. For short pulses, GELINA's flux is $\sim 1/2$ of the ORELA unprebunched value. For long pulses, GELINA's smaller stored energy limits its flux to ~ 0.3 of the ORELA value.

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*It is assumed that the prebuncher will compress an on-target 40-J (2×10^9 n/J) 15-ns-wide pulse to 4 ns. (See Section IX for a brief description of the prebuncher.)

Table 5. Comparison of "White" Neutron Sources for TOF Measurements

	ORELA	HELIOS (Ly80)	GELINA (Be81)	WNR (Au80)	PSR (Au80)
		Short-Pulse Mode for keV-MeV TOF Measurements			
Pulse-width (ns)	4	5	4	0.2	1.0
10^{10} neutrons/pulse	8[a]	1.1	1.9	0.2	120
Pulses/s	1000	2000	900	6000	720
10^{13} neutrons/s	8[a]	2.2	1.7	1.3	86
		Long-Pulse Mode for meV-eV TOF Measurements			
Pulse-width (ns)	40	40[b]	11	3000[c]	270
10^{10} neutrons/pulse	13	12	4.3	130	45000
Pulses/s	1000[d]	1000[d]	900[d]	120	12
10^{13} neutrons/s	13	12	3.9	16	540

[a]Without the prebuncher, ORELA can produce 3 x 10^{10} neutrons in a 5-ns pulse, giving 3 x 10^{13} neutrons/s at a repetition rate of 1000 pps.

[b]HELIOS has several targets and operating modes (Ly80).

[c]For TOF measurements above 1 eV, the experimental resolution would be significantly degraded by this pulse width. The FWHM of a hydrogenous moderator resolution function is approximately $2\mu s/\sqrt{\text{neutron energy in eV}}$.

[d]These pulse repetition rates are rarely used for measurements involving thermal neutrons. To avoid pulse overlap on a 10-m flight path requires a pulse rate less than 100 pps.

Except for small differences caused by electron energy and target materials and very appreciable differences caused by moderator materials and design, these three electron linacs give similar neutron spectra and have many similarities in their cross-section measurement programs. At present, GELINA is already a very productive facility, while HELIOS is not yet at full output. While the research programs at these facilities differ in emphasis, the international replication of research results permitted by the facilities allows important nuclear data to be verified.

The WNR facility utilizes LAMPF's 800-MeV proton beam, which is structured for neutron TOF measurements to give either 200-ps or 3-μs-wide proton pulses onto a tantalum target. The 3-μs-wide pulses are mostly useful only in the low-eV region and below. The short 200-ps pulses coupled with the relatively large number of higher-energy neutrons produced from 800-MeV protons gives WNR a larger figure of merit (FOM) than ORELA for measurements at neutron energies above a few MeV (Ra70); however, the operating time that can be devoted to this mode is limited. FOMs are designed to estimate relative source effectiveness as a function of neutron energy for experiments in general; however, for any particular experiment a quite different relative effectiveness may apply. The PSR, an extension to LAMPF and the WNR facility, is scheduled for completion in the mid 80's and will permit 1-ns and 270-ns pulses with two to three orders of magnitude more neutrons than the present WNR pulses. The 270-ns pulse will be nearly 4000 times more intense than the ORELA 40-ns pulse. The 1-ns pulse will be more than ten times as intense as the ORELA 4-ns pulse, giving 100-fold and 1000-fold larger FOMs than ORELA at 2 and 20 MeV, respectively. It is not yet clear whether this superior pulsed source will be available for more than an occasional nuclear physics or applied data study (since it is proposed for condensed matter studies in addition to weapons-related research).

Similar conclusions about the relative performance of these sources in terms of FOM as a function of neutron energy are given by Auchampaugh (Au80). Other factors are also significant in comparing the utility of these TOF facilities. The large capital investment at ORELA in low-background beam lines, samples, detector systems, and computer equipment provide the means for superior measurements. The importance of full operating schedules and staffing levels cannot be overestimated. Nevertheless, over the next decade ORELA will require an aggressive accelerator development program or replacement with a more intense source if it is to remain dominant for a broad range of experiments.

IX. FUTURE FACILITY IMPROVEMENTS

This section first reviews how demands on a pulsed neutron source vary with the neutron energy region in which measurements are being made. It then describes accelerator and computer facility improvements under consideration for the ORELA facility. Finally, it discusses the possibility of replacing ORELA with a proton accelerator.

A. Neutron Energy Ranges of Interest

From the preceding discussions of ORELA measurements, the energy ranges of most interest for the various research areas may be inferred. These can be summarized as follows:

The range between ~0.01 and 1 eV is important for condensed matter physics research and studies of neutron reactions important to thermal reactors. The effects of condensed matter phenomena on apparent neutron cross sections is of scientific interest. "Time-frame overlap" limits the useful repetition rate to 100 pps or less unless very short flight paths can be used.* (At 0.01 eV, neutron velocity is about 1.4 km/s.) Below 0.2 eV, the (neutron source) moderator component of the resolution is strongly affected by the "upscatter" due to thermal motion unless a reduced-temperature or poisoned moderator is employed.

The range between ~1 eV and ~20 keV is the region for study of resonance phenomena, including those in heavy nuclides important to both thermal and fast reactors. Here there is little competition for facilities with pulsed "white" sources. The moderators which must be used in the neutron sources induce a FWHM resolution of about 2 $\mu s/\sqrt{E(eV)}$, equivalent to a flight-path uncertainty of about 3 cm (Pe75, Ru77). For this reason it is not important here to have fast-neutron source pulses narrower than about 10 ns. Time-frame overlap inhibits high repetition rates because the flux detectors used have high efficiency at low energies, and boron absorbers introduced to attenuate the lower energy flux also affect intensity throughout this region of interest. The efficiency characteristic of the flux detectors also inhibits the use of ^{238}U electron targets because of delayed neutron detection.

The range between ~20 keV and ~3 MeV is important for resonance studies in medium-weight nuclides (including structural materials) and for studies of unresolved resonance and smooth cross sections in the heavier

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*For *nuclear* measurements below 1 eV, particularly with room-temperature samples, a 2- or 3-meter flight path would provide adequate resolution and a repetition rate of ~400 pps could be used. At ORELA, there is no useful provision for flight paths less than 10 meters.

nucides, such as the fuel materials of fast fission reactors. This region is also of importance for fusion reactors. Highest resolution studies in the MeV region have great potential for broadening the "window" for study of nuclear excited states. Many experiments can be performed using liquid or plastic scintillators or other detectors unresponsive at lower energies, and neutron moderators are not required in the neutron source. Energy resolution is usually limited by the accelerator pulse width, and the effective intensity per pulse is limited by the need to shield the detector system from the gamma-ray "flash" from the target. (NOTE: In this energy region, electron linacs compete with "monoenergetic" neutron sources, the choice depending on the purpose of the experiment as well as on the energy.)

The range between ~3 and ~60 MeV can be subdivided. Up to 15 MeV the data for the ever-increasing number of open reaction channels are of importance for fusion reactors, and over the whole range the studied reactions have importance for applications, for example, to the design and use of the D-Li source of the Fusion Materials Irradiation Test Facility. Many n-charged particle reactions can be studied, resonance structure of the lighter nuclides can be defined, and at the higher energies one can study shape-elastic scattering as a function of energy (directly and via the total cross sections). Resolution again depends on the pulse width, and usable intensity depends on both the pulse width and the amount of gamma-flash attenuation required. Whenever detector system pileup limits the burst strength, the overall effective intensity is proportional to the accelerator repetition rate.

The neutron spectrum from a beryllium target peaks in the 10- to 20-MeV energy region, whereas the spectrum from a tantalum target peaks at about 1 to 2 MeV. In the upper part of this region, the intensity for a given target power depends on the electron energy. Though the forward-hemisphere neutrons from a spallation source would provide a more favorable spectrum in this energy region than do those from an electron linac, many reactions are accessible to study at ORELA in this energy range.

In considering what energy ranges should be emphasized with any improvements to ORELA, the following points appear to be the most important:

(1) ORELA does not produce enough power per pulse to provide a "world-class" source for condensed matter studies, but limited work could be performed and the source intensity could be increased by up to a factor of two were this energy region to be emphasized. Some nuclear experiments would benefit from the increased intensity in this region (Pe75).

(2) For most experiments using neutrons above 10 keV, the intensity even at ORELA has been a restriction. Above this energy there has usually been a compromise between resolution and counting rate in the experimenter's selection of accelerator pulse width. This problem is alleviated as the instantaneous accelerated electron current is increased.

(3) ORELA experiments can make a significant contribution in the MeV neutron energy range, but intensity and resolution are now important constraints. Increasing the peak current in short pulses and arriving at an optimum design of a beryllium target would offer improvement, but the target neutron spectrum provides limited intensity in this energy region.

(4) The productivity of ORELA depends strongly on the long operating schedules and on the multiple flight paths that permit concurrent experiments.

B. Upgrading ORELA

Opportunities exist for development of the ORELA machine and facility to permit maximum sustained output. A number of such efforts have been considered and are listed below. They concern (1) the machine itself, (2) facilities for developing and testing machine components, and (3) flight-path and experiment stations for improved neutron utilization. Note that most are designed to achieve on a routine basis the ORELA performance quoted in Section VIII.

Higher Klystron Output Power. It is known that 3-GHz klystrons recently developed at SLAC attain up to 40-MW peak power with thermal efficiencies upwards of 45% (Ko81). Tallerico reports a 353-MHz klystron with ~60% efficiency and 500 kW *cw* power output (Ta79). We have procured from Litton Inc., our klystron supplier, a feasibility analysis of design modifications to our klystrons to yield a 40-MW peak power with 55% efficiency at our 1.3-GHz frequency. The study (Bo81) did indicate feasibility and used a computer program that correctly describes the performance of the tubes presently used. Such tubes would permit the stored energy to be increased by 1/3 with a small input power decrease. The maximum electron energy should then be greater than 200 MeV. It is believed that the rf windows to the accelerator waveguides and the guides themselves could tolerate the increased fields. The next step would be to purchase a prototype with the higher performance modification to test the validity of the revised design.

Electron Guns with Increased Current. The ongoing electron gun development program is producing guns with improved reliability and increased protection against grid emission (Ch81). However, these guns of revised design have not been tested at full output because of failure in the cathode drive pulse (see below). Attempts to increase current through more drastic design changes require improved test facilities if the risk of extensive down time is to be avoided.

The "grounded" (at ~130 kV) grid triode gun depends on steep ~2500-V drive pulses to its cathode to define the ORELA electron pulse shape. These pulses have been produced from thyratron pulses through a difficult-to-analyze combination of transmission-line shaping networks that depend on the nonlinear, breaking wave behavior from ferrite dielectric (Ka66). For the past few years, adequate short-pulse drive cannot be achieved because of afterpulses that would produce erroneous experimental results, and we have not determined what design or fabrication change caused this degradation. (Present shaping networks do have longer life than previous versions.) Hard-tube pulsers are now marketed that should provide superior performance, and delivery of such a pulser is expected soon. Parallel strong efforts are underway to recover or improve on the previously experienced level of clean-pulse performance from the present type of pulser.

Electron Prebuncher. Electron guns of the presently used design seem to yield pulsed output no greater than 40 A. About half of this current is accelerated. To improve short-pulse performance, an ~15-ns pulse can be compressed to about a 4-ns width by applying differential acceleration/deceleration potentials to various time segments of the electron pulse from the gun. This expectation is based on the work of Alsmiller *et al.* (A179). Experimenters requiring medium neutron intensity could then share beam time with those who require narrow time resolution, and the latter could enjoy enhanced intensity. An Accelerator Improvement Project in 1975-78 (ND74) was completed to take advantage of this opportunity. However, quality failures from chloride stress-corrosion cracking occurred in the kovar vacuum seals of the ferrite-loaded "gap" cavity structures interposed between the electron gun and the accelerator. While bunching action has been demonstrated, the full system has only now become available for test. (A new set of cavities was constructed using a revised design that requires no corrosive flux.) A goal is to place the new system in productive use by September 1982. This goal may be met if full system tests do not show a need to design complex auxiliary devices.

Electron Beam Injector Laboratory. At present the ORELA staff is unable to test detailed properties of its electron guns even though the angular spread from the gun is expected to affect prebuncher performance. Moreover, until complete tests can be performed on each gun prior to use, we are not able to estimate expected performance. A 1983 General Plant Project is proposed to construct a second-floor extension to the ORELA building to provide clean room and other spaces needed for electron gun production and testing. The same GPP project will provide room suitable for off-line testing and development of the entire electron injector system of the accelerator. This test system would eventually include at least the provision of short pulses and part or all of a prebuncher system with the necessary diagnostics. The project goal is to provide appropriate facilities in which the staff can work to attain consistent design-level performance of the critical electron injector system.

500-meter Flight Station. In order to facilitate high-resolution studies that reveal all the structure important to cross-section applications and also to permit physics inquiry over a broader region of excitation energy, a much longer flight path is required than the 200-meter path presently available at ORELA. (The first advantage could be attained by use of a thinner neutron-producing target and thinner detectors, but a thinner target would impair the multiple use of the neutron source.) Preliminary plans called for an earth-covered 16-in.-diameter evacuated tube extending Flight Path 1 to a small flight station about 500 meters from the target. Since current cost estimates amount to about $800 K, the project has been set aside.

Other Improvements. A preliminary investigation of the feasibility of greater automation in the operation of ORELA is planned, both to increase availability of the operator for other tasks and potentially to increase average output through more frequent optimization of parameters.

Considerable work is required to improve the beam monitors now in use at ORELA and to add additional ones to permit better understanding of beam conditions than is now possible.

The possibility of obtaining a neutron-producing target optimized for the low-eV region has been considered repeatedly without reaching a conclusion. Since a significant portion of ORELA time is devoted to runs at low repetition rates for low-energy cross sections, these target analyses should be brought to a conclusion. Similarly, there is doubt whether the beryllium block target sometimes used to emphasize production of high-energy neutrons (Bo70) is appropriately designed to optimize higher-energy neutron production for general use.

There is frequent contention for use of flight paths and stations, particularly for those paths nearly normal to the target moderator surface. Facilities have not been provided for flight paths shorter than 10 meters, and those at 20 meters are difficult to develop for low-energy transmission measurements. In this case, no specific proposals for improvement have been made.

C. Improving Data-Acquisition and Immediate-Analysis Systems

Data-Acquisition System. The present common data-acquisition system at ORELA accepts partially derandomized streams of 28-bit "events" from each active experimenter. Each of three data-acquisition computers can accept these event descriptors from up to four experimenters so long as the total number of channels of mass storage on that computer is not exceeded and the total data rate in that computer is less than about 5 K disc storage increments per second. Prior to incrementing the contents of one or more of the mass-store channels, the computer performs a prescribed mapping of the event descriptors onto a designated storage region on the specially organized fixed-head disk. The three computers have, respectively, bulk storage capacities of about 0.35 M, 0.7 M, and 1.0 M sixteen-bit words. A similar computer (called the PEC) manages peripheral equipment and computer interconnections. The acquisition system (Be69, Re77) usually operates well, but is becoming increasingly hard to maintain because of hardware obsolescence. In addition, it has a storage capacity and a data acceptance rate that are now too small, and it is rather inflexible in its interaction with individual experiments.

A prototype development effort is underway to permit phased extension and then replacement of this data-acquisition system. Two types of newly designed equipment are being constructed: Bulk Storage Units and Experiment Access Units. Each Bulk Storage Unit consists primarily of a CAMAC crate with controller, an appropriate microcomputer, and 2 M sixteen-bit words of bulk core memory. Each user will communicate to a storage unit through a slot in the CAMAC crate, and will provide in appropriate format the list of addresses of storage cells to be incremented. Alternative access to the data bank will permit "dumping" results to tape, to disc drives on the Immediate Analysis Computer System, or for display. Channel-number streams will be accommodated from the current acquisition computers, direct from an experimenter's gear, or from whatever other source. Electrical ground isolation will be best accomplished if the CAMAC module receives the data along a glass fiber. A draft specification manual for the prototype unit is expected to be provided soon, and prototype hardware components are available.

While some experimenters already have effective "private" experiment access units that can be used to drive these storage units, initial design is underway of a general-purpose Experiment Access Unit based on a flexible microcomputer. Such a unit should not only provide the translation between the partially derandomized stream of experimental event descriptors and the bulk storage channel to be incremented, but it should also provide the needed degree of experimental equipment control, diagnostic logging, display, and whatever else is needed by the experimenter to help keep a complex set of equipment under control. As indicated above, each Experiment Access Unit would communicate with a Bulk Storage Unit, preferably by a fiber optic link.

As presently designed, Bulk Storage Unit hardware costs ~\$70 K in a 2 M 16-bit word size, and a minimum Experiment Access Unit should cost about \$30 K. While the capital cost of prototype hardware can be accommodated in the normal equipment budgets, a special funding effort may be required to replace entirely the aging DAC computers when the prototypes have been completed and proven. A problem may arise in supporting the programming effort required for achieving the needed flexibility and ease of use of the Experiment Access Units. (Several years of programming effort were expended on the DAC system now becoming obsolete.)

Immediate-Analysis Computer System. ORELA experimenters and analysts must manipulate and have quick graphic access to the large data arrays generated in their experiments and in successive data analysis steps. A PDP-10 system with significant disk storage and special graphic capabilities is located at ORELA and functions well to meet this need, but is now obsolete (Wi73). One must question whether future performance improvements should be obtained through continuing incremental changes to this machine or whether a large step should be taken.

The KA-10 processor now has access to 240 K 36-bit words of fast memory, about 400 megabytes of removable disc pack storage, four high-speed graphic terminals based on PDP-15's, about 25 other terminals, two difficult-to-maintain tape drives, and efficient high-rate communication to the peripheral equipment and storage units of the data-acquisition system. While the monitor and programming structure approach the ideal from the user point of view, both the computing speed and the on-line common disc store have often been inadequate as analysis needs have become more complex.

A preliminary study of an appropriate replacement focussed on the possibilities of upgrading the present system significantly, including dual processors; or, alternatively, replacing the entire existing system with a contemporary design with about double the capability (in speed and storage size) at a cost nearing \$400 K. These options must be analyzed further, taking into account future needs, changeover costs, maintenance, etc.

D. Replacing ORELA Neutron Source

The ORELA facility is capable of producing $\sim 10^{14}$ fast neutrons per second (n/s) at 1000 pps and is presently the international leader in obtaining neutron cross-section data for applied and basic research programs. In order to assure the maximum research efficiency and the capability to satisfy neutron data needs in the future, particularly those for fusion reactor systems, basic physics in the 10- to 200-MeV range, and perhaps condensed matter physics, the possible options for an ORELA-replacement neutron source are actively being studied. It is important to know whether the limitations of ORELA could be overcome at a cost in balance with the potential research program or through construction of a facility shared with condensed matter research and a "cold" demonstration of electronuclear fuel production. The objective of this study is to obtain the best available preliminary conceptual design for a pulsed "white" neutron source with a spectrum-averaged hundred-fold improvement over the figure of merit (FOM) of ORELA for TOF measurements. With optimized pulse widths and repetition rates, this desired hundred-fold improvement might be achieved with a ten-fold increase in average neutron source strength, to 10^{15} n/s. Power dissipation probably prevents this goal from being achieved with an electron accelerator using a compact target even if the required electron beams could be generated.

A combination of moderated and unmoderated spallation neutrons from protons in the 200- to 300-MeV range on a heavy metal target seems best to meet the intensity objective. Alsmiller *et al.* (Al81) have calculated that 190- to 268-MeV protons on an ORELA-like tantalum target would produce 0.018*[E(MeV)-113] fast neutrons per proton, so that one 230-MeV proton would produce two neutrons. [Therefore, target energy dissipation per neutron would be about 5% of that experienced with the present electron beam.] In addition, the low proton beam power could allow the convenient use of a ^{238}U target which would provide an estimated two-fold increase in neutron production per proton over tantalum for those experiments not sensitive to the delayed-neutron background from fission. In this case a 10^{15} n/s (avg) source would require ~20 kW of target power for 200- to 300-MeV protons. Moreover, a 230-MeV proton produces approximately 400 times as many 20-MeV neutrons and 1400 times as many 50-MeV neutrons, averaged over 4π steradians, as a 150-MeV electron. (Normalized to the same integral neutron source strength, the 230-MeV protons produce 10 and 35 times as many 20- and 50-MeV neutrons, respectively, as 150-MeV electrons, and in the forward hemisphere the advantage is much larger.) Finally, the gamma-flash problem of electron linac targets would be substantially eliminated and the alternative would exist to produce approximately monoenergetic $^7Li(p,n)$ neutrons in the forward direction. The results of Alsmiller *et al.* show more efficient neutron production for protons above ~200 MeV, whereas the desire for a compact target and negligible meson-produced background suggest a proton energy less than ~300 MeV. At forward angles, the high-energy neutrons would tend to produce backgrounds in measurements at lower energies.

The combinations of pulse widths and pulse periods useful for TOF measurements with thermal to 200-MeV neutrons are infinite in number, but some bounds can be given. The minimum useful pulse width for MeV neutrons is limited by the detector resolving time. For commonly used detectors with present technology this resolution is in the 0.5- to 1.0-ns range. For slower neutrons, accelerator pulse widths narrower than the moderator time spread do not improve resolution; accelerator pulse widths narrower than approximately 1 $\mu s[E(eV)]^{-1/2}$ are therefore irrelevant to the experimental resolution for hydrogen-moderated neutrons with energies less than E. Equally time-spaced pulses are most useful. For fast neutrons a maximum repetition rate of at least 1000 pps, the present ORELA rate, would be extremely desirable. For TOF measurements below 1 eV, 100 to 200 pps has usually been a maximum useful rate.

An obvious candidate for an ORELA replacement neutron source could be based on the technology of the 600-MeV PIGMI proton linac designed by LANL for medical applications (Bo80). This short-duty-cycle accelerator is compact, efficient, remarkably simple, and has an estimated cost of ~\$10 M. Its microbursts are ~0.2-ns wide, are spaced by 2.3 ns, and each contains 4×10^8 protons at the design current. One micropulse accelerated to 270 MeV and incident on a uranium target would produce 2.3×10^9 neutrons, 30 times fewer neutrons than the maximum from an ORELA bunched 4-ns pulse. (Note that the latter has not yet been realized.) A train of three micropulses would have the ORELA short-pulse width and produce about one-tenth the neutrons. However, a 1-μs train of these micropulses for condensed matter studies would produce 1×10^{12} fast neutrons, a factor of ten more than the ORELA 35-ns pulse. The PIGMI-design rf system would apparently allow ~300 micropulses or micropulse trains per second and require 0.2 MW of rf. (It would take an accelerator with ten times the design current of PIGMI and three times its design rf duty cycle to equal ORELA'S FOM in the energy range 10 to 100 keV. Such a hypothetical source would have an FOM nearly two orders of magnitude larger than ORELA's for condensed matter and fusion cross-section studies. However, since it is believed that a RFQ accelerator section at the frequency used in PIGMI could not accelerate ten times the design charge per pulse (St81), this simple hypothetical accelerator is not feasible.)

Present conventional proton linac designs as exemplified by PIGMI are unable to directly produce the pulse intensities, without a storage ring, required for an ORELA-replacement neutron source, even with extremely optimistic extrapolation of performance parameters. Although the time-averaged current from these accelerators is sufficient, this current is not structured into widely separated intense short pulses suitable for neutron TOF measurements. The LANL Accelerator Technology Division has completed for ORNL a conceptual design study of a proton linac optimized for neutron TOF measurements. As summarized below, this neutron source would give a spectrum-averaged hundred-fold FOM improvement over ORELA. Their complete report is reproduced in Appendix C.

This conceptual design consists of a 40-MHz RFQ structure, followed by 80- and 160-MHz Alvarez drift-tube structures, and would be capable of accelerating micropulses containing 2×10^{11} protons up to 200 MeV. The ion source at 200 keV is visualized to be a multiaperture dual pigatron giving 2A peak, 1-μs-wide pulses at 1000 pps from an array of 7×7 beamlets. A fast helical chopper similar to that of LAMPF would be used to select single micropulses for subsequent acceleration. These micropulses would be bunched and accelerated to 5 MeV with a 14-meter-long, 1.6-meter-diameter, 40-MHz RFQ. The drift tube structures would be 107 meter long requiring 6 MW of rf power with the 80- to 160-MHz frequency transition at 40 MeV. The output beam spot would be 1.5×3 cm and contain 95% of the protons in a pulse width of 0.9 ns. This beam, incident onto an ORELA-like target with uranium plates, would produce 6×10^{11} neutrons per isolated micropulse. Alternatively, one micropulse could be accelerated every 25 ns with up to 40 micropulses in a micropulse train. The maximum rate would be 1000 micropulse trains per second.

This accelerator concept would permit an extremely powerful and flexible neutron source. A single micropulse would produce nearly 10 times the fast neutrons of an ORELA prebunched 4-ns pulse. This pulse intensity plus the short pulse width, the reduced gamma-flash, and the spectral advantage for proton-produced neutrons would combine to give this source an FOM at least 10^3 larger than that of ORELA at fusion-system energies and above. For condensed-matter studies, 1-μs trains of these micropulses would produce 250 times more neutrons than an ORELA 35-ns pulse. At 300 pps this accelerator would provide a world-class spallation source of 1×10^{16} fast neutrons per second if a uranium target can be used. Without engineering and development, building construction, contingency, and escalation, this accelerator was estimated to cost nearly $50 M (FY1981).

The appreciable capital cost plus the large power cost (8 MW avg of rf) estimated for this conceptually designed proton linac suggest that more cost-effective schemes should be sought to obtain a similar performance for neutron TOF measurements. A promising approach may be to feed a small storage ring with a PIGMI-like accelerator, and the LANL Accelerator Technology Division is expected to perform for ORNL a feasibility study of such options. In addition, "circular" accelerators may deserve exploration because they may conserve accelerator structures and rf power. Induction linacs and pseudo-random-binary-sequence pulsed conventional accelerators also deserve some study.

In summary, a conceptual design exists for a proton linear accelerator neutron source which would provide a hundred-fold FOM improvement over ORELA. However, this accelerator would be large and would be expensive compared to the research program so-far envisioned. The options for a more cost-effective neutron source with similarly high performance are actively being studied.

X. CONCLUSIONS AND RECOMMENDATIONS

Since no other accelerator in the U.S. is devoted exclusively to obtaining "applied" nuclear data and to studying the basic physics of neutron-nucleus reactions, it is recommended that the work at ORELA continue at a vigorous pace through the next decade. The range of data covered is sufficiently broad that at least some data measured at ORELA are pertinent to the design of any nuclear facility. Thus there should be demand for ORELA measurements, and the necessary financial support should be available under a variety of scenarios of U.S. energy development and research support. If the Proton Storage ring at LAMPF also becomes available for some studies in these areas, its use (by ORNL staff) should be considered for those experiments that would most demand its capabilities.

After a very successful first decade of ORELA research, extra energy should now be devoted to a renewal both of the facility and of ideas for using it. If a cost-effective replacement accelerator could be constructed with significantly increased capability, that concept should be explored; however, since implementing the replacement would require several years, efforts to attain improved productivity from ORELA should also be emphasized. Should a replacement accelerator eventually be proposed, its potential for application to condensed matter research should be carefully considered. An internal decision is planned by the end of 1982.

Of the possible improvements proposed in Section IX, the ORELA staff believes that all should be undertaken except possibly the addition of the 500-meter flight station (deleted for economic reasons). Continued investigation may indicate some reordering of priorities and/or emphasis of the other developments listed. For example, "conventional wisdom" of computer system renovation suggests that, since the basic need exists for an upgraded dedicated computer for the next decade of research, replacement will be more cost effective than major renovation of the present system, but conventional wisdom could be in error because of unusual compatibility problems. Table 6 gives the schedule envisioned for the major hardware improvements that are recommended. Considerable planning effort by the research staff will be required.

Because of the nature of most ORELA experiments, it is more economical to operate the accelerator at all times not required for maintenance. Because of this and because as much as a 12-month experiment backlog is frequently experienced, an operating schedule of 38 shifts per 14-day period should replace the present 29 shifts per 14-day period.

To permit the concurrent development and enhanced operation programs planned, an additional experienced engineer has recently been added to the ORELA staff. It is hoped that technical assistance to make full use of the proposed Electron Beam Injector Laboratory can be made available economically through the partial automation of the accelerator.

In addition to the equipment development discussed above, full benefit from ORELA as a unique neutron source requires a vigorous research staff. Recent efforts to increase the interactions of the staff with nuclear theorists and experts in the forefront on techniques of data analysis should continue. Also, an increase in junior scientific and technical staff assigned to aid research would be cost effective. Finally, the value of ORELA could be enhanced by an increased level of research participation by university scientists in the

Table 6. Schedule for ORELA Development Projects

Item	FY 81	FY 82	FY 83	FY 84	Comments
Pulsed-gap prebuncher					
a. New gaps delivery.		▲			
b. Installation.		▲			
c. Operating trials, pulse refinement.		▭			Day-shift tests to begin 2-82.
d. Effective use.		△			Completion on schedule depends on whether additional hardware is required.
Electron Beam Injector Laboratory (1983 GPP proposal)					
a. "Criteria" document, including preliminary estmate.	▲				ORELA development staff will provide criteria and justification; preliminary cost estimate was $660 K; $500 K now allocated.
b. Funding decision.		△			
c. Develop "conceptual design."		▭			FY 82 expense of $25 K for engineering.
d. Complete construction.				△	
ORELA replacement study					NOTE: Study to be guided by Committee of Olsen, Horen, and Martin.
a. Single-pulse (proton) linac feasibility.		▲			Completed by LANL.
b. Storage ring study.		△			LANL available.
c. "Final" committee report.		△			Cyclotron-synchrotron part of study may be incomplete.
d. Decision on proposal submission.			△		Depends on feasibility plus some sponsor encouragement.
Higher efficiency klystron					
a. Feasibility.	▲				Positive per Litton study.
b. Procurement and test of prototype.		▭	▭		
c. AIM project for full installation.				▭	
Data Acquisition System bulk storage units					
a. Performance and interface specifications.		△			
b. Software development.		▭	▭		
c. Prototype unit in limited service.		△			Requires SEL connection.
d. Bulk storage unit report.			△		Hardware and software, tests, maintenance and operation manual.
e. Construct second and third units				▭	Exact schedule depends on equipment funds availability.
f. Retire or off-line original storage devices.				△	Retirement date depends also on storage needs and maintenance status.

Table 6. Continued

Item	Schedule FY 81	FY 82	FY 83	FY 84	Comments
Data Acquisition System experiment access units					
a. Preliminary design and operation specifications.		△			Research staff.
b. Procure major hardware for prototype.		△			
c. Preliminary tests.			▬		Use device on a relatively simple experiment.
d. Software development			▬	▬	
e. Prototype in full service				△	
f. Procure additional units as needed.			▬	▬	
Replacement or upgrade of Immediate Analysis Computer System					
a. Preliminary conceptual design and justification.		△			Define and justify goals; consider compatibility problems.
b. Request for preliminary quotation.		△			To obtain accurate cost and avoid missing major alternatives.
c. Final conceptual design and justification.			△		To finalize request.
d. Procurement.				▬	
e. Phase-in.				▬	

more physics-oriented portions of the work. Unfortunately, the arduous effort associated with analysis of the large data sets obtained at ORELA is not matched to the needs of university scientists with modest amounts of available research time.

Overall, the ORELA plan provides a coordinated but flexible route toward achieving a strengthened facility and a more powerful research effort. Such gains are desired to help achieve national nuclear data goals and to take advantage of unique physics research opportunities.

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APPENDIX A

LIST OF ORELA GUESTS AND COLLABORATORS

Throughout the operation of ORELA, a number of individuals have joined the facility's research staff in the performance of experiments. This appendix lists those persons and indicates their areas of investigations. The list includes both those who have worked essentially independently and those who have worked as collaborators with our staff. Whenever the time in Oak Ridge was brief, the time spent reducing the data at the home institution was usually lengthy.

LIST OF ORELA GUESTS AND COLLABORATORS

Users or Guests	Institution	Years of Visits	Total Residence Time	Short Research Title	An ORNL Contact
M. M. Moore	San Fernando Valley State C.	1968	3 mo	Autocorrelation techniques for subthreshold structure	Perez
H. Derrien	Saclay, France	1968-69	6 mo	Multilevel analysis ^{235}U and ^{239}Pu	de Saussure
A. Mockel	U. Florida	1969	1 mo	General formalism of T-matrix	Perez
R. W. Benjamin	Savannah River	1971-5	2 mo	Total cross section	Harvey
J. L. Rodda	U. W. Virginia	1971	2 mo	Electron beam profile	Macklin
J. Vitkevitch	Clarkson Col.	1971	2 mo	Electron beam profile	Macklin
B. J. Allen	AAEC, Australia	1971-4	31 mo	Many capture cross sections	Macklin
M. C. Taylor	Houston, TX	1971	1 mo	Proton recoil flux monitor	Macklin
O. A. Wasson	BNL	1971	12 mo	Valence neutron capture	Slaughter
R. R. Winters	Denison U.	1971-81	45 mo	Many capture cross sections	Macklin
R. F. Carlton	Middle Tn. St.	1971-81	10 mo	Neutron capture and total	Raman
G. A. Keyworth M. Anaya F. Seibel	LANL " "	1972-4 " "	7 mo " "	Spins of U-235 and Np-237 resonances using polarized neutrons and aligned targets	Dabbs
F. Simpson O. Simpson	Idaho Nucl. "	1972 "	3 mo "	Total cross sections "	Harvey "
G. Bartholomew	Chalk River	1972	0.5 mo	Tl-205 total and capture cross sections	Harvey
D. Earle	Chalk River	1972	1 mo	Neutron capture gamma spectra	Slaughter
A. Namenson	NRL	1972	1 mo	Neutron capture gamma spectra	Slaughter
R. E. Chrien	BNL	1972	1 wk	Neutron capture	Slaughter
M. S. Moore	LANL	1972	1 wk	Fission experiments	Dabbs
A. Ellis	LANL	1972	1 wk	Fission experiments	Dabbs

Users or Guests	Institution	Years of Visits	Total Residence Time	Short Research Title	An ORNL Contact
L. A. Galloway	Centenary Col.	1972	3 mo	Total cross sections	Johnson
H. Roesler	U. Munich	1972	2 mo	^{236}U fission cross section	Schmitt
W. Kolar	BCMN, Geel	1972	1 mo	^{235}U resonance analysis	de Saussure
J. R. Smith	Idaho Nuclear	1972	1 wk	Resonance analysis technique	de Saussure
G. Van Praet	U. Antwerp	1972	4 mo	Strontium isotope capture	Macklin
C. E. Ahlfeld	Savannah River	1971-2	2 wk	Total cross sections	Harvey
H. G. Miller	Idaho	1972-4	3 mo	Total cross sections	Harvey
M. A. Lone	Chalk River	1972	0	Neutron capture gamma spectra	Slaughter
A. Stolovy	Naval Res. Lab.	1973	4 wk	Capture spectra	Harvey
G. D. James	Harwell	1973	12 mo	^{234}U total and fission cross sections	Dabbs
T. R. Chang	Taiwan	1973	2 mo	Total cross sections	Harvey
C. E. Olsen	LANL	1973	1 wk	Spin experiments	Dabbs
B. Teasdale	LANL	1973	2 wk	Time digitizers	Hill
S. F. Mughabghab	BNL	1974	1 mo	Neutron capture gamma spectra	Slaughter
R. C. Byrd	BNL	1974	1 wk	Total cross section	Harvey
G. W. Cole	BNL	1974	1 wk	Total cross section	Harvey
L. Remez	Argentina	1974-5	2 yr	Development of detector electronics	Ingle
J. B. Garg	SUNY-Albany	1974-81	6 mo	Mn, Cu, Zn, isotopic and capture	Macklin
S. Jain	"	1975	1 wk		"
B. Leurs	Columbia U.	1975-7	1 yr	Properties of ^{235}U fission resonances	Harvey
J. P. Felvinci	"				
E. Melkonian	"				
T. Walkiewicz	Edinboro Col.	1975-81	5 mo	Decay of In isotopes	Raman

Users or Guests	Institution	Years of Visits	Total Residence Time	Short Research Title	An ORNL Contact
H. Weigmann	BCMN, Geel	1975	8 mo	Magnesium total and isotopic capture	Harvey Macklin
F. C. Difilippo	CNEA, Argentina	1975-7	2 yr	Subthreshold ^{238}U fission cross section	Perez
R. Nelson	LANL	1976	2 mo	Total cross section	Harvey
M. S. Pandey	SUNY-Albany	1976	1 mo	Cu-63, Cu-65 total and capture cross sections	Harvey
C. LeRigoleur	France, AEC	1976	4 mo	Ni-58, Ni-60 total and capture cross section	Macklin
D. A. McClure	Georgia State	1977	1 mo	^{143}Nd(n,γ) reaction	Raman
J. R. Harvey	CEGB, Berkley	1977-8	2 wks	Total cross section	Harvey
M. Mizumoto	Japan, AEC	1977	15 mo	Tm, Y, Pb-206 capture	Raman
G. A. Auchampaugh	LASL	1977-81	2 mo	Pu-240 subthreshold fission Np-237 total	Weston
C. Renner	Brazil	1977	1 yr	^{6}L(n,α) absolute cross section	Harvey
S. Plattard	Bruyeres le Chatel	1977-81	6 mo	Angular distribution of fission fragments	de Saussure
J. J. Malanify	LASL	1978	0.6 mo	Ir, Lu, Tm capture	Macklin
J. H. Hamilton	Vanderbilt	1978	0.1 mo	Neutron spectroscopy of Pb-206	Raman
E. Kjartansfsson	Denison U.	1978	1 mo	Capture cross sections	Macklin
D. M. Drake	LASL	1978-81	1 mo	Ir, W, Lu, Tm capture cross section	Macklin
C. Bowman	NBS	1979	1 wk	Neutron detectors	Gwin
L. Morton	Denison U	1979	0.5 mo	Capture cross sections	Macklin
P. Lisowski	LASL	1979	0.2 mo	Capture cross sections	Macklin
J. W. Boldeman	AAEC	1979	0.1 mo	Y et al. capture cross sections	Macklin

Users or Guests	Institution	Years or Visits	Total Residence Time	Short Research Title	An ORNL Contact
M. R. Meder	U. Georgia	1979	0	Theoretical calculations of Sn levels	Raman
O. Shahal	Israel	1979-80	1 yr	$^{173}Yb(n,\gamma)$ reaction	Raman
B. Fogelberg	Sweden, AEC	1980	3 mo	Kr-86 transmission and capture	Raman
F. Froehner	Karlsruhe	1980	2 mo	Advanced data analysis techniques	Perey
S. Kahane	Israel	1980-1	1 yr	$^{167}Er(n,\gamma)$ reaction	Raman
A. R. Hussein	Egypt	1980	12 mo	Total cross sections	Harvey
P. K. Mukhopadhyay	BARC	1980-1	1 yr	Development of detector electronics	Ingle
J. Munoz-Cobos	U. Valencia	1980-1	1 yr	U-238 capture cross sections and self-indication ratio	Perez
B. Castel	Queen's U.	1980-1	3 wks	Theoretical interpretation	Raman
J. T. Wang	Taiwan	1980-1	1 yr	U-238 capture cross sections and self-indication ratio	Perez
W. M. McDonald	U. Maryland	1981	4 wks	Theoretical interpretation	Johnson
M. L. Wood	Georgia Tech.	1981	1 mo	Calibration of liquid scintillator	Raman
H. Beer	Karlsruhe	1981	0.5 mo	Hafnium isotopic capture	Macklin
M. Lacerna	Denison U.	1981	1 mo	Capture cross sections	Macklin

APPENDIX B

BIBLIOGRAPHY OF ORELA-RELATED PUBLICATIONS

March 1982

This appendix consists of a bibliography of the research performed at ORELA up to March, 1982. It is divided into the following sections:

Many papers include information on more than one of the above topics; most have been listed under the first category indicated in the paper's title. With each category, papers are listed in chronological order, most recent first, if no isotope is mentioned in the title. Those papers mentioning specific isotopes are listed by the atomic weight of the first isotope in the title, in ascending order.

In order to be included here, a paper or report had to be dependent on data from ORELA, or on closely related work by ORELA research staff during the ORELA time period. Titles of abstracts and summaries of oral presentations are intended to be excluded. Cross-section evaluation reports are included when they involve expertise and/or data dependent on ORELA. As a result of these ground rules, many papers by ORELA staff have been excluded.

1. NEUTRON CAPTURE CROSS SECTIONS*

MACKLIN, R. L. AND R. R. WINTERS
Corrigendum, "Stable Isotope Capture Cross Sections from the Oak Ridge Electron Linear Accelerator"
Nucl. Sci. Eng. 78, 110-11 (1981)

MACKLIN, R. L.
"Resonance Capture Reactions with a Total Energy Detector"
Third International Symposium on Neutron Capture Gamma-Ray Spectroscopy, Upton, New York, September 1978; pp. 475-84 in Neutron Capture Gamma-Ray Spectroscopy, Plenum Press, New York, 1979

MACKLIN, R. L., R. R. WINTERS, AND J. HALPERIN
"Recent Capture Cross Section Data from ORELA above 2.6 keV"
NEANDC Specialists' Meeting on Neutron Cross Sections of Fission Product Nuclei, Bologna, Italy, December 1979 pp. 103-12 in CONF-791223, 1979

MUSGROVE, A. R. DE L., B. J. ALLEN, J. W. BOLDEMAN, AND R. L. MACKLIN
"Recent Measurements of Neutron Capture Cross Sections in the Fission Product Mass Region"
International Conference on Nuclear Data for Reactors and Other Applied Purposes, Harwell, England, September 1978; pp. 449-71 in Proceedings, OECD Nuclear Energy Agency, 1978

BOLDEMAN, J. W., B. J. ALLEN, M. J. KENNY, A. R. DE L. MUSGROVE, AND R. L. MACKLIN
"Valence and Doorway State Effects in Neutron Capture Near Closed Shells"
Third National Soviet Conference on Neutron Physics, Kiev, USSR, June 1975; pp. 233-48 in Proceedings, Vol. 3, ed. V. P. Vertisinii et al., Moscow, U.S.S.R., 1976

WESTON, L. W.
"Neutron Capture Cross Sections of the Actinides"
Advisory Group Meeting on Transactinium Isotope Nuclear Data, Karlsruhe, Germany, November 3-7, 1975; pp. 15-20 in IAEA-186, Vol. 2, 1976

MACKLIN, R. L.
"Neutron Capture in Reactor Structural Materials"
NEACRP/NEANDC Specialists' Meeting, Karlsruhe, FRG, May 1973; pp. 63-72 in Neutron Capture in the keV Energy Range in Structural Materials for Fast Reactors, Report KFK-2046, 1975

*Many papers include fission cross sections.

1. NEUTRON CAPTURE CROSS SECTIONS (cont.)

WESTON, L. W. AND J. H. TODD
"Measurement of the Neutron Capture Cross Sections of the Actinides"
Conf. on Nuclear Cross Sections and Technology, Washington, D.C., March 3-7, 1975; p. 229 in NBS Spec. Publ. 425, 1975

ALLEN, B. J. AND R. L. MACKLIN
"ORELA Neutron Capture and Stellar Nucleosynthesis"
Atomic Energy in Australia 16, 14-21 (1973)

ALLEN, B. J. AND R. L. MACKLIN
"Neutron Capture Cross Sections of C-13 and O-16"
Phys. Rev. C 3(5), 1737-40 (1971)

MACKLIN, R. L. AND R. R. WINTERS
"Neutron Capture in Fluorine below 1500 keV"
Phys. Rev. C 7(5), 1766-1769 (1973)

ALLEN, B. J. AND R. L. MACKLIN
"Fast Neutron Capture Cross Sections for Silicon"
Proceedings International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, March 1973; pp. 291-92 in USAEC Conf-73-0301, ed. B. L. Berman, 1973

ALLEN, B. J., A. R. DE L. MUSGROVE, D. M. H. CHAN, AND R. L. MACKLIN
"Neutron Capture Cross Sections of the Calcium and Barium Isotopes"
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APPENDIX C

CONCEPTUAL DESIGN STUDY OF A PROTON LINEAR ACCELERATOR TO REPLACE ORELA*

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*AT-1-81-290

I. Introduction

This is a report on a conceptual design study for a proton linear accelerator, which could replace the ORELA neutron facility at Oak Ridge. The study was motivated by the hope that recent developments in ion linac technology, most notibly the success with the Radio-Frequency Quadrupole (RFQ) linac, might make possible a proton linear accelerator system which could be competitive or superior to the existing electron linac facility.

Our main goal for this study was to design the best linear accelerator that would accelerate protons to 200 MeV in single bunches at a 1 kHz bunch rate. The desired single bunch intensity was 5×10^{11} protons per bunch. The beam spot size at the output was to be less than 1 to 1.5 inches in diameter. The time width of the output bunch was to be less than 1 ns.

Among the various ideas and designs that were developed, we have presented in this report the details of the design that seemed to us the most promising. For this design we have carried out a computer simulation for the linac itself and we have tried to briefly identify the areas that we felt might require development.

One problem that was encountered early in the study was the necessity for obtaining a high enough peak current from existing ion sources to match the capability of the linac. Our proposed solution in this report is to develop a pulsed ion source with a high peak current capability. Another idea, that was tried but rejected, was to use a conventional ion source with low peak current, followed by a very low frequency RFQ, as a prebuncher before the main RFQ. However, the resulting RFQ prebuncher was excessively long (about 40 to 50 m) due to the requirement for high current limit at very low energies, together with the very low frequency operation needed.

Another idea, which was sucessfully implemented for this study, was a method for allowing frequency transitions to higher frequency linacs, without relying entirely on adiabatic damping of the beam bunch to permit injection into the new smaller buckets. This idea is discussed in more detail in Section VI on the drift tube linac.

We begin this report with a general description of the accelerator system in Section II. Sections III, IV, V, and VI, give specific details about the accelerator components. Section VII summarizes the results of the computer simulation of the linac portion of the accelerator system. The rf power requirements are evaluated in Section VIII and the cost estimate is presented in Section IX. Section X presents a summary and some conclusions.

II. Description of Accelerator System

A block diagram of the accelerator system which formed the basis of this study is shown in Fig. 1. We propose that the ion source can be a scaled up version of a Duopigatron source with a multiaperture extraction column of the type that has been developed at Chalk River.[1] The source would consist of a 7 x 7 array of beamlets to give a peak H^+ output beam current of 2A at an output energy of 200 keV. If the extraction electrodes were pulsed at a 1 kHz rate, the desired beam bunch frequency could be obtained with a relatively low average beam current. A reasonable minimum value for the pulse width is estimated to be about 1 μs,[2] which would imply a source duty factor of about 10^{-3}.

Since the separation of adjacent buckets in the rf linacs will be a few tens of nanoseconds, it will be necessary to employ some kind of fast beam chopper in order to pre-select one bunch and reject adjacent bunches within each relatively wide ion source pulse. Here we propose to use a fast beam chopper of the type developed at Los Alamos.[3,4] This beam chopper is currently being used in the low energy beam transport at LAMPF to select one micropulse, where the adjacent bunch centroids are separated by only 5 ns. If the chopper system is placed immediately after the ion source, the beam immediately downstream of the chopper slits will ideally consist of narrow pulses, whose time width equals the rf period of the RFQ linac, which follows.

These beam pulses are then injected into an RFQ linac,[5] which bunches and accelerates them from 200 keV to 5 MeV. The RFQ is an ideal transition accelerator between the dc ion source and the drift tube linac. The use of the RFQ allows the dc output voltage to remain relatively low, eliminates the need to a separate buncher, and gives a higher injection energy into the drift tube linac. As a result, a large aperture can be used at the input to the

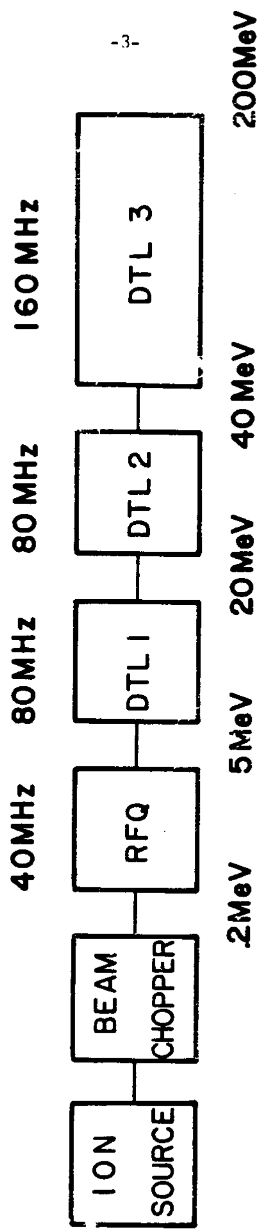

Fig. 1. Block Diagram Of The Accelerator System

drift tube linac, which is necessary for a high beam current capacity. At high injection energies this large aperture can be used, without the transit time factor reduction and subsequent loss of acceleration rate, which is characteristic of lower energy injection. Since the current limit bottleneck of the overall linear accelerator system still occurs in the RFQ, the choice of RFQ parameters is critical in determining this maximum beam current.[6] Among these parameters, the injection energy, the rf frequency, the final synchronous phase, and the energy at the end of the bunching section are carefully chosen to maintain a higher beam current capacity. This results in the relatively low frequency of 40 MHz for the RFQ.

The bunched output beam from the RFQ can be injected into an Alvarez drift-tube linac. The drift-tube linac parameters should of course, be chosen to give a large effective shunt impedance, which means that high accelerating fields result for a given input power. Since the shunt impedance increases with the square root of the rf frequency, it is desirable to design the drift tube linac for high frequency operation, consistent with the requirement of high beam current capability. The transition from the low 40 MHz frequency of the RFQ to higher drift tube linac frequencies must be done gradually. We have chosen to make these transitions in factors of two. The phase length of the beam bunch in each linac decreases adiabatically. When the phase length has decreased sufficiently it becomes possible to double the frequency and to transfer the beam bunch into the new smaller buckets with little accompanying beam loss. It is primarily this requirement of providing adequate longitudinal phase acceptance as the frequency is increased, that determines the energies at which the frequency doublings can be made. For this design example there are two drift tube linac frequencies beginning with 80 MHz and doubling to 160 MHz at 40 MeV. The 160 MHz drift tube linac accelerates the beam to a final energy of 200 MeV. It could be continued to give higher final energies if desired.

A high energy beam transport system could be used if necessary to accept the 200 MeV beam and focus it onto the final target with an optimum transverse spot size. The detailed design of a final beam line has not been included in this study.

III. Ion Source

In anticipation of the high current limit of the linear accelerator system, which results from the introduction of the RFQ for the low beta portion of the linac, it is necessary to provide an ion source with large peak current. Since the beam current bottleneck occurs within the RFQ, the overall design procedure began with the RFQ, which is discussed in more detail in Section V. The resulting RFQ imposes the important requirements on the ion source. The RFQ peak current limit is 3.1A of H^+ within the normalized acceptance of $\epsilon = 8.3\pi$ cm–mr. We anticipate that the actual operating current will be about 2A. The resulting input RFQ energy is 200 keV. For a 1 kHz beam pulse rate, we assume that the source will provide a pulsed beam rather than a dc beam. A pulsed source allows a reduction in the power supply capacity as well as a reduction in the cooling requirements. A pulsed 2A source would probably require development. We propose as an attractive candidate the duopigatron source with a multiaperture extraction column such as has been developed at Chalk River. The measurements made on the seven-aperture source have shown beams with 40.5 mA per beamlet within an effective normalized emittance of about 0.1π cm–mr per beamlet. The latter number includes the geometrical dilution factor. The quoted emittance corresponds to 95 percent of the beam of which 70 percent is estimated to be H^+. In order to obtain 2A of H^+ we obtain a required 7 x 7 array, whose corresponding normalized emittance would be 4.9π cm–mr.

The pulsed beam could be obtained by pulsing the extractor electrodes. A pulse rate of 1 kHz could be imposed and a pulse width as small as about 1 μs seems feasible. The average beam current would be no more than several millamperes. A pulse width of 1 μs would still be much larger than the desired pulse width of a micropulse at the input to the RFQ, which is 25 ns. This smaller pulse width could be obtained by use of a fast beam chopper as described in Section IV. A summary of the assumed properties of the ion source is given in Table 1.

Table I

Summary of Assumed Properties of Ion Source

Peak Beam Current of H^+ (A)	2
Effective Normalized Emittance (cm–mr)	4.9π
Output Energy (keV)	200
Pulse Rate (kHz)	1
Pulse Width (μs)	1

IV. Fast Beam Chopper

If the beam pulse length from the ion source is of the order of 1 μs and if the required beam pulse length to fill one and only one rf bucket at the input to the RFQ is 25 ns, it will be necessary to use a fast beam chopper. The beam chopper used at LAMPF consists of a pair of helical delay lines installed on opposite sides of the beam axis, and whose propagation directions are parallel to the beam. When pulses of opposite charge are injected into the two delay lines, a transverse electric field is produced across the beam. The geometry of the delay lines is chosen so that the axial propagation velocity of the transverse electric field is equal to the beam velocity.

A dc bias voltage can be superimposed across the delay lines so that in the absence of the fast pulses the beam is given a transverse deflection away from a downstream slit. When the fast charge pulses are introduced, the dc field can be canceled and the wanted beam pulse can be transmitted through the slit. The width and rise time of the injected charge pulse must be chosen to optimize the requirements for maximum transmission of the desired micropulse and maximum rejection of the unwanted adjacent micropulses. Although we have assumed that the chopper would be placed before the RFQ, an alternate approach would be to use the chopper after the RFQ. For the latter approach, the chopper could deflect an already bunched beam. In principle, this has the advantage of allowing both good transmission and a cleaner separation of the unwanted pulses in the presence of a finite rise time of the chopper. It would have the disadvantages associated with deflecting a higher energy beam at 5 MeV.

There has not been time in this study to answer the question of whether the chopper system should be located before or after the RFQ. We have also not had time to try to design a chopper which could meet the requirements for this high-peak beam current application. For the purposes of this study we have assumed that the chopper system behaved in an ideal way to transmit all particles in the wanted bunch with no emittance increase, and to reject all particles in adjacent bunches.

V. Radiofrequency Quadrupole (RFQ) Linac

Since the current limit bottleneck occurs in the RFQ the accelerator system design began with the RFQ. It is believed from studies of beam current limitations in linacs, that parametric resonance effects limit the strength of the transverse focussing, that can be applied to counteract the space charge defocussing. This limitation is expressed in terms of a maximum value of $\sigma_0 = \pi/2$, where σ_0 is the transverse phase advance per focusing period at zero beam current. We have chosen to design the RFQ at this limit so as to be able to accelerate a maximum peak beam current. The aperture is chosen as large as is possible within the allowed stability limits, when the non-linear terms in the transverse rf defocus effect are included. The choices of synchronous phase angle and energy at the end of the bunching section, where the current limit occurs, were made as a compromise to obtain reasonably large values, which increase the current limit; but not so large as to make the RFQ length excessively great. The bunching section was chosen to end at 2.2 MeV and the synchronous phase at this point and beyond was chosen as -38°. The degree of modulation of the vanes was chosen to balance the longitudinal and transverse current limits, to obtain an optimized space charge design. The injection energy of 200 keV was chosen to be as low as was allowed by the requirememts for large final synchronous phase angle with our design algorithms, and for stability in the presence of the non-linear rf defocus terms. The final energy was chosen to allow a high injection energy into the drift tube linac, so that a large drift tube aperture could be used with minimum reduction in the initial drift tube linac acceleration rate. Furthermore, as will be discussed in more detail in Section VI, the final energy must be chosen high enough so that the adiabatic damping of the longitudinal phase width of the bunch is sufficient to permit an rf frequency doubling into the drift tube linac. However, too high a final energy results in inefficient acceleration from the RFQ. The choice of 5 MeV for a final RFQ energy seems to be a resonable compromise. At a peak surface field of 17.5 MV/m, which seems to be experimentally acceptable in the low frequency range, the maximum operating rf frequency is then determined by the previously discussed requirement that $\sigma_0 = \pi/2$. We obtain an operating frequency of about 40 MHz. The RFQ was then designed using the usual design algorithm developed at Los Alamos for high space charge applications.

The RFQ parameter summary is listed in Table 2. The resulting peak current limit was 3.1A. We usually find that good performance can be obtained for operating beam currents of about half the current limit and no more than about two thirds the current limit. We choose a nominal peak current of 2A. This corresponds to the current averaged over one rf period of 25 ns, and it corresponds to about 3.1×10^{11} protons per bunch.

The RFQ peak power is the peak power dissipated within the RFQ cavity. This was calculated assuming a 4-vane RFQ cavity, which is driven without a coaxial rf manifold. The inner diameter of the 4-vane cavity at 40 MHz would be about 1.6 m.

A complete list of parameters for this RFQ design as generated by the computer code PARMTEQ, is presented in Table 3.

In order to avoid beam envelope oscillations within the RFQ, which can lead to radial beam loss on the vanes, it is desirable to provide a matched beam for the RFQ. This is done by the use of focussing elements in the low energy beam transport system, between the ion source and the RFQ. These focussing elements would be designed to provide a specific matched configuration for the transverse beam ellipse at the input to the RFQ. Also, near the output of the RFQ the vanes can be perturbed in order to provide a matched beam for the drift tube linac. For the purposes of this study we have ignored any modifications resulting from beam matching requirements, since we believe they will have a minor effect on the overall performance and cost.

Table 2

RFQ Design Parameter Summary

Ion	H^+
Frequency (MHz)	40
Input Energy (MeV)	0.20
Output Energy (MeV)	5.00
Peak Surface Field (MV/m)	17.5
Peak Current Limit (A)	3.1
Nominal Peak Current (A)	2.0
Nominal Protons per Bunch	3.1×10^{11}
Normalized Acceptance (cm-mr)	8.3π
Initial Synchronous Phase (deg)	-90°
Final Synchronous Phase (deg)	-38°
Final Modulation Parameter	2.25
Average Radius (cm)	6.18
Length (m)	14.4
Peak Power (MW)	5.4

TABLE 3

PARMETQ LISTING FOR RFQ

loak5 ,freq= 40.00 mhz, q=1.0,wi= .200,wf= 5.00 i=2000.0ma page 1

tank 1 length= 1436.28 cm, 119 cells, charge state 1.

nc	v	ws	beta	ex	capa	phi	a	m	b	rfd	cl	tl
1	.798	.200	.0206	0.000	0.000	-90.0	27.648	1.000	.83	0.00		
1	.798	.200	.0206	0.000	0.000	-90.0	11.528	1.000	3.59	0.00	7.74	7.74
2	.798	.200	.0206	0.000	0.000	-90.0	8.531	1.000	6.56	0.00	7.74	15.47
3	.798	.200	.0206	0.000	0.000	-90.0	7.079	1.000	9.53	0.00	7.74	23.21
4	.798	.200	.0206	0.000	0.000	-90.0	6.181	1.000	12.50	0.00	7.74	30.94
5	.798	.200	.0206	.009	.001	-90.0	6.171	1.003	12.51	-.01	7.74	38.68
6	.798	.200	.0207	.019	.002	-90.0	6.162	1.006	12.51	-.02	7.74	46.42
7	.798	.200	.0207	.028	.003	-90.0	6.153	1.009	12.51	-.03	7.74	54.15
8	.798	.200	.0207	.037	.004	-90.0	6.144	1.012	12.51	-.04	7.74	61.89
9	.798	.200	.0207	.046	.004	-90.0	6.135	1.015	12.51	-.04	7.74	69.63
10	.798	.201	.0207	.055	.005	-90.0	6.127	1.018	12.51	-.05	7.74	77.36
11	.798	.201	.0207	.065	.006	-90.0	6.118	1.021	12.51	-.06	7.74	85.10
12	.798	.201	.0207	.074	.007	-90.0	6.109	1.024	12.51	-.07	7.74	92.83
13	.798	.201	.0207	.083	.008	-90.0	6.100	1.027	12.51	-.08	7.74	100.57
14	.798	.201	.0207	.092	.009	-89.8	6.092	1.030	12.51	-.09	7.74	108.31
15	.798	.201	.0207	.101	.010	-89.7	6.083	1.033	12.51	-.10	7.74	116.06
16	.798	.201	.0207	.110	.011	-89.5	6.075	1.036	12.51	-.10	7.74	123.80
17	.798	.201	.0207	.118	.011	-89.4	6.067	1.039	12.51	-.11	7.75	131.55
18	.798	.201	.0207	.127	.012	-89.2	6.058	1.042	12.51	-.12	7.75	139.29
19	.798	.202	.0207	.136	.013	-89.1	6.050	1.045	12.51	-.13	7.75	147.04
20	.798	.202	.0207	.145	.014	-88.9	6.042	1.048	12.51	-.14	7.75	154.79
21	.798	.202	.0208	.154	.015	-88.7	6.034	1.050	12.51	-.15	7.75	162.55
22	.798	.203	.0208	.163	.016	-88.6	6.026	1.053	12.51	-.15	7.76	170.30
23	.798	.203	.0208	.172	.017	-88.4	6.018	1.056	12.51	-.16	7.76	178.07
24	.798	.203	.0208	.180	.018	-88.3	6.010	1.059	12.51	-.17	7.77	185.84
25	.798	.204	.0208	.189	.018	-88.1	6.002	1.062	12.51	-.18	7.78	193.61
26	.798	.204	.0209	.198	.019	-88.0	5.994	1.065	12.51	-.19	7.78	201.40
27	.798	.205	.0209	.207	.020	-87.8	5.986	1.068	12.51	-.20	7.79	209.19
28	.798	.205	.0209	.216	.021	-87.6	5.978	1.071	12.51	-.20	7.80	216.99
29	.798	.206	.0210	.225	.022	-87.5	5.970	1.074	12.51	-.21	7.81	224.80
30	.798	.207	.0210	.234	.023	-87.3	5.962	1.077	12.51	-.22	7.82	232.62
31	.798	.208	.0210	.243	.024	-87.2	5.955	1.080	12.51	-.23	7.84	240.46
32	.798	.209	.0211	.252	.025	-87.0	5.947	1.083	12.51	-.24	7.85	248.31
33	.798	.209	.0211	.261	.026	-86.8	5.939	1.086	12.51	-.24	7.87	256.18
34	.798	.211	.0212	.268	.027	-86.7	5.933	1.089	12.51	-.25	7.88	264.06
35	.798	.212	.0212	.275	.027	-86.5	5.928	1.091	12.51	-.26	7.90	271.96
36	.798	.213	.0213	.282	.028	-86.4	5.922	1.093	12.51	-.26	7.92	279.88
37	.798	.214	.0214	.289	.029	-86.2	5.917	1.095	12.51	-.27	7.94	287.83
38	.798	.215	.0214	.296	.030	-86.0	5.911	1.097	12.51	-.27	7.97	295.80
39	.798	.217	.0215	.303	.030	-85.9	5.906	1.099	12.51	-.28	7.99	303.79
40	.798	.218	.0216	.310	.031	-85.7	5.900	1.102	12.51	-.28	8.02	311.80
41	.798	.220	.0216	.317	.032	-85.5	5.895	1.104	12.51	-.29	8.05	319.85
42	.798	.222	.0217	.325	.033	-85.4	5.889	1.106	12.51	-.30	8.07	327.92
43	.798	.224	.0218	.332	.034	-85.2	5.883	1.108	12.51	-.30	8.11	336.03
44	.798	.225	.0219	.339	.035	-85.0	5.878	1.110	12.51	-.31	8.14	344.17
45	.798	.228	.0220	.347	.036	-84.9	5.872	1.113	12.51	-.31	8.17	352.35
46	.798	.230	.0221	.355	.037	-84.7	5.867	1.115	12.51	-.32	8.21	360.56
47	.798	.232	.0222	.363	.038	-84.5	5.861	1.117	12.51	-.32	8.25	368.81
48	.798	.235	.0224	.371	.039	-84.4	5.855	1.119	12.51	-.33	8.29	377.10
49	.798	.237	.0225	.379	.040	-84.2	5.850	1.122	12.51	-.33	8.34	385.44
50	.798	.240	.0226	.387	.041	-84.0	5.844	1.124	12.51	-.34	8.38	393.82
51	.798	.243	.0227	.395	.042	-83.9	5.838	1.126	12.51	-.34	8.43	402.25
52	.798	.246	.0229	.404	.043	-83.7	5.832	1.129	12.51	-.35	8.48	410.73
53	.798	.249	.0230	.411	.044	-83.5	5.828	1.130	12.51	-.35	8.54	419.27
54	.798	.252	.0232	.416	.045	-83.3	5.825	1.131	12.51	-.35	8.59	427.86
55	.798	.256	.0233	.421	.046	-83.2	5.822	1.132	12.51	-.36	8.65	436.51

*

TABLE 3

(CONT'D)

56	.798	.260	.0235	.426	.046	-83.0	5.819	1.134	12.51	-.36	8.71	445.88
57	.798	.263	.0237	.431	.047	-82.8	5.817	1.135	12.51	-.36	8.77	453.99
58	.798	.267	.0239	.436	.048	-82.6	5.814	1.136	12.51	-.36	8.84	462.82
59	.798	.271	.0240	.441	.049	-82.4	5.811	1.137	12.51	-.36	8.90	471.73
60	.798	.276	.0242	.446	.050	-82.3	5.808	1.138	12.51	-.36	8.97	480.70
61	.798	.280	.0244	.452	.051	-82.1	5.805	1.139	12.51	-.37	9.05	489.75
62	.798	.285	.0246	.457	.052	-81.9	5.802	1.140	12.51	-.37	9.12	498.87
63	.798	.290	.0249	.462	.053	-81.7	5.799	1.141	12.51	-.37	9.20	508.07
64	.798	.295	.0251	.468	.054	-81.5	5.795	1.142	12.51	-.37	9.28	517.34
65	.798	.301	.0253	.473	.056	-81.3	5.792	1.143	12.51	-.37	9.36	526.71
66	.798	.306	.0255	.479	.057	-81.1	5.789	1.145	12.51	-.37	9.45	536.16
67	.798	.312	.0258	.485	.058	-80.9	5.786	1.146	12.51	-.37	9.54	545.69
68	.798	.318	.0260	.490	.059	-80.7	5.782	1.147	12.51	-.37	9.63	555.32
69	.798	.325	.0263	.496	.060	-80.5	5.779	1.148	12.51	-.37	9.72	565.04
70	.798	.331	.0266	.501	.062	-80.3	5.776	1.149	12.51	-.37	9.82	574.86
71	.798	.338	.0268	.505	.063	-80.1	5.774	1.150	12.51	-.37	9.92	584.78
72	.798	.345	.0271	.508	.064	-79.9	5.772	1.150	12.51	-.37	10.03	594.81
73	.798	.353	.0274	.511	.065	-79.7	5.771	1.151	12.51	-.37	10.13	604.94
74	.798	.360	.0277	.515	.066	-79.5	5.769	1.151	12.51	-.37	10.24	615.18
75	.798	.368	.0280	.518	.067	-79.3	5.767	1.152	12.51	-.36	10.35	625.53
76	.798	.377	.0283	.521	.068	-79.1	5.765	1.152	12.51	-.36	10.47	636.00
77	.798	.385	.0286	.524	.070	-78.9	5.763	1.153	12.51	-.36	10.59	646.59
78	.798	.394	.0290	.528	.071	-78.7	5.761	1.153	12.51	-.36	10.71	657.30
79	.798	.403	.0293	.530	.072	-78.4	5.759	1.154	12.51	-.35	10.83	668.13
80	.798	.413	.0297	.533	.073	-78.2	5.757	1.154	12.51	-.35	10.96	679.10
81	.798	.423	.0300	.536	.075	-78.0	5.755	1.155	12.51	-.35	11.09	690.19
82	.798	.433	.0304	.539	.076	-77.8	5.753	1.156	12.51	-.35	11.23	701.41
83	.798	.443	.0307	.542	.077	-77.5	5.751	1.156	12.51	-.34	11.36	712.78
84	.798	.454	.0311	.544	.078	-77.3	5.749	1.157	12.51	-.34	11.50	724.28
85	.798	.466	.0315	.551	.081	-76.8	5.744	1.159	12.51	-.34	11.66	735.94
86	.798	.479	.0319	.563	.084	-75.9	5.734	1.162	12.51	-.34	11.84	747.78
87	.798	.493	.0324	.576	.087	-75.1	5.723	1.166	12.51	-.34	12.00	759.79
88	.798	.508	.0329	.588	.090	-74.2	5.713	1.170	12.51	-.34	12.18	771.97
89	.798	.525	.0334	.601	.093	-73.3	5.702	1.174	12.51	-.34	12.38	784.35
90	.798	.543	.0340	.613	.097	-72.4	5.692	1.178	12.51	-.34	12.59	796.94
91	.798	.563	.0346	.625	.100	-71.5	5.681	1.182	12.51	-.34	12.81	809.75
92	.798	.585	.0353	.637	.104	-70.5	5.669	1.186	12.51	-.34	13.05	822.80
93	.798	.608	.0360	.656	.109	-69.4	5.652	1.193	12.51	-.34	13.32	836.12
94	.798	.635	.0368	.678	.116	-68.1	5.631	1.201	12.51	-.34	13.61	849.73
95	.798	.665	.0376	.701	.122	-66.9	5.609	1.209	12.51	-.34	13.92	863.64
96	.798	.698	.0385	.722	.129	-65.6	5.587	1.218	12.51	-.34	14.25	877.89
97	.798	.735	.0395	.747	.137	-64.2	5.561	1.228	12.51	-.34	14.62	892.51
98	.798	.776	.0406	.781	.147	-62.6	5.527	1.242	12.51	-.34	15.02	907.53
99	.798	.823	.0419	.814	.158	-61.0	5.491	1.256	12.51	-.34	15.46	922.99
100	.798	.876	.0432	.853	.170	-59.4	5.448	1.273	12.51	-.34	15.94	938.93
101	.798	.937	.0447	.901	.186	-57.6	5.394	1.295	12.51	-.34	16.47	955.40
102	.798	1.007	.0463	.953	.204	-55.8	5.332	1.321	12.51	-.34	17.06	972.46
103	.798	1.087	.0481	1.014	.225	-53.8	5.256	1.353	12.51	-.34	17.72	990.18
104	.798	1.181	.0501	1.089	.252	-51.8	5.161	1.394	12.51	-.34	18.45	1008.62
105	.798	1.292	.0524	1.174	.284	-49.7	5.046	1.446	12.50	-.34	19.27	1027.89
106	.798	1.423	.0550	1.277	.323	-47.5	4.899	1.514	12.51	-.34	20.19	1048.08
107	.798	1.579	.0579	1.400	.373	-45.2	4.710	1.607	12.51	-.35	21.24	1069.32
108	.798	1.769	.0613	1.649	.436	-42.8	4.461	1.738	12.51	-.35	22.44	1091.76
109	.798	2.001	.0652	1.733	.517	-40.3	4.119	1.940	12.51	-.35	23.81	1115.57
110	.798	2.287	.0697	1.933	.614	-38.0	3.674	2.248	12.51	-.35	25.37	1140.94
111	.798	2.598	.0743	1.850	.620	-38.0	3.662	2.248	12.51	-.31	26.75	1167.69
112	.798	2.912	.0786	1.756	.626	-38.0	3.649	2.248	12.51	-.28	28.44	1196.12
113	.798	3.228	.0827	1.675	.630	-38.0	3.638	2.248	12.51	-.25	30.03	1226.16
114	.798	3.545	.0867	1.604	.634	-38.0	3.630	2.248	12.51	-.23	31.55	1257.71
115	.798	3.864	.0905	1.540	.637	-38.0	3.623	2.248	12.51	-.21	33.01	1290.72
116	.798	4.183	.0941	1.484	.640	-38.0	3.617	2.248	12.51	-.20	34.41	1325.14
117	.798	4.504	.0976	1.433	.642	-38.0	3.613	2.248	12.51	-.18	35.76	1360.90
118	.798	4.825	.1010	1.387	.644	-38.0	3.608	2.248	12.51	-.17	37.06	1397.96
119	.798	5.147	.1043	1.345	.646	-38.0	3.605	2.248	12.51	-.16	38.32	1436.28

*

VI. Drift Tube Linac

The drift tube linac accepts the bunched beam from the RFQ at 5 MeV and performs the major job of accelerating that beam to the final energy, which was 200 MeV in this study. In order to keep the overall cost low, it is necessary to choose a cell geometry which accomplishes this task as efficiently as possible. The common figure of merit used to characterize this efficiency is the effective shunt impedance per unit length, ZT^2, which is a function of the cell geometry. We have chosen a cell geometry as a function of beam velocity, which was optimized for high ZT^2 for the PIGMI project at Los Alamos, using the program SUPERFISH. This specific data will be presented in tabular form later in this section.

An important result that is determined from any given choice of cell geometry is the ratio of peak surface electric field to the peak axial electric field. Then, given a value of peak surface field which is allowable from the point of view of sparking, the axial electric field is determined. It is generally believed that the maximum allowable values of peak surface field depend upon frequency. The values assumed for our design will be presented later in this section.

The drift tube linac will use magnetic quadrupoles to provide the transverse focusing. We have chosen a FODO lattice configuration (where the quadrupole polarity alternates in each sequential drift tube). We have assumed a filling factor (ratio of quadrupole effective length to cell length) of 50 percent for the first cell, and we have assumed quadrupoles of constant length and constant strength within each drift tube tank.

Because the effective shunt impedance increases as the square root of rf frequency, it is desirable to operate the drift tube linac at high frequency for reasons of efficiency. The RFQ operating frequency is rather low (40 MHz), and it is attractive to try to begin operation of the drift tube linac at a higher frequency. However, higher frequency operation implies a smaller time interval for the stable bucket. Frequency transitions must be made carefully in order to minimize possible particle loss associated with injection of the beam into the smaller bucket. We will now describe the method used to make the frequency transitions.

As is well known, if the acceleration in a previous stage is carried to high enough energy, the bunch phase width will decrease adiabatically. In practice, this process is very slow so that, if the synchronous phase parameter, which determines the bucket phase width, were unchanged at the frequency transition, it would require a large energy gain before you could, for example, double the frequency without particle loss. Instead we propose to use a different approach, which we call the phase jump method. The idea is to increase the initial magnitude of the synchronous phase at the new frequency to a value large enough so that the phase width of the new bucket is somewhat larger than the phase width of the beam. Also, the phasing of the new accelerator tank is chosen so that the centroid of the bunch arrives at the center of the stable bucket, rather than at the synchronous phase. As a guide in the choice of the initial synchronous phase angle, we have used the well established relation between synchronous phase and bucket width at zero beam current. The choice of initial synchronous phase angle could presumably be optimized through numerical simulation procedures to take into account the space charge perturbation to this basic relationship.

Having begun the initial synchronous phase for the new frequency at a relatively large magnitude, to obtain good capture of the beam bunch, we then ramp it to smaller value as rapidly as possible in the new section in order to return to a good acceleration rate, while maintaining adequate longitudinal focusing.

In practice, it seems to us that the optimum way to maximize the overall accelerator efficiency by the use of frequency transitions, is to combine the adiabatic damping method with the phase jump method. This combined approach eliminates the need for the excessive energy gain required for the pure adiabatic damping approach, and it eliminates the need for the large synchronous phase increase required for the phase jump approach.

It is desirable to make frequency transitions in integer steps so that the bunch structure from the previous accelerator output will remain in synchronism with the bucket structure after the frequency transition. The choice of frequency doubling is the smallest increase that can be made consistent with this constraint. We have assumed that a sequence of frequency doublings results in an optimum solution for the drift tube linac.

We have chosen to make the first frequency transition at 5 MeV where the beam leaves the 40 MHz RFQ and enters an 80 MHz Alvarez drift-tube linac. In order to maintain a high effective shunt impedance we have used two different basic cell-geometry solutions for the 80 MHz drift tube linac. For both solutions the geometrical parameters vary with particle velocity. The first cell-geometry solution is used from 5 MeV to 20 MeV and can be characterized by a fixed inner diameter of the cylindrical tank of 253 cm. The second cell-geometry solution is used from 20 MeV to 40 MeV and is characterized by an inner diameter of the cylindrical tank of 220 cm. At 40 MeV we have found that a second frequency transition to 160 MHz is possible. The 160 MHz linac can be extended to the final energy of 200 MeV. At 160 MHz a high effective shunt impedance results from only one cell geometry solution for the cell parameters as a function of velocity. The inner diameter of the cylindrical tank for this solution is 110 cm. Figure 2 gives the definition of the cell geometry parameters. Tables 4, 5, and 6 give the cell geometry parameters over the entire drift tube linac. Also given in these tables is the effective shunt impedance ZT^2, the Q, and the ratio to peak surface electric field to the axial accelerating field, E_s/E_0.

For the 80 MHz drift tube linac, we have chosen a peak surface field of E_s = 17 MV/m (at the input). From the last entry in Table 4, this implies an axial field of E_0 = 2.585 MV/m, which we assume will be constant throughout tank I. Similarly, the same restriction on the peak surface field at the input to tank 2 yields an axial field in tank 2 of 2.347 MV/m. We assumed a peak surface field at 160 MHz of 23.8 MV/m. Applying this at the end of the 160 MHz linac we obtain an axial field E_0 = 3.66 MV/m. The bore radius, r_b=4.5 cm in Tables 4, 5, and 6 was chosen to give adequate transverse acceptance of the relatively large space-charge dominated beam bunch.

In order to minimize beam loss on the radial aperture of the drift tubes, it is necessary to maintain a matched beam within each accelerating structure; thereby eliminating oscillations of the beam envelope. This means that specific beam ellipse parameters must be provided at the input to each new accelerating structure. We propose to perturb the focusing elements near the output of a previous structure to obtain the correct matched ellipse

solution at the input of each new structure. Thus, at the end of a drift tube linac the quadrupole gradient can be perturbed. At the end of the RFQ the radial aperture of the vanes can be tapered. As was stated earlier, we have ignored any modifications resulting from beam matching requirements, since we believe they will have a minor effect on the overall performance and cost estimates.

A summary of the design parameters for the drift tube linac is presented in Table 7. The power listed is the peak power dissipation in the Alvarez cavity including a correction for losses on stems.

A complete list of parameters for the 80 MHz drift tube linac design, as generated by the computer code PARMILA is given in Table 8. Table 9 contains the same information for the 160 MHz drift tube linac.

VII. Linac Beam Dynamics Simulation and Output Beam Characteristics

A numerical simulation was made of the beam dynamics of the RFQ and the drift tube linac, using the computer codes PARMTEQ for the RFQ and PARMILA for the drift tube linac. For this simulation we assume that a matched beam is presented at the input to the RFQ by the ion source and the low energy beam transport. The programs PARMTEQ and PARMILA trace particles which are generated with random initial coordinates. Both the effects of external focusing forces and internal space charge forces are included. The calculated output includes the transmission through the accelerator and the emittance of the beam. Plots of the phase space configuration of the beam at each cell and projections of variables versus cell number are provided.

Ideally, the overall linac performance could be simulated by randomly generating an initial distribution at the RFQ input, and by transporting these same particles through the RFQ and through the drift tube linac. Instead, it turned out to be faster and more convenient to do the simulation in three steps. First, the beam with the input characteristics summarized In Table I was transported through the RFQ to an energy of 5 MeV using PARMTEQ. In order to continue the simulation we have used the transverse emittance for the 90 percent contour (the central 90 percent of the beam) at the output of the RFQ

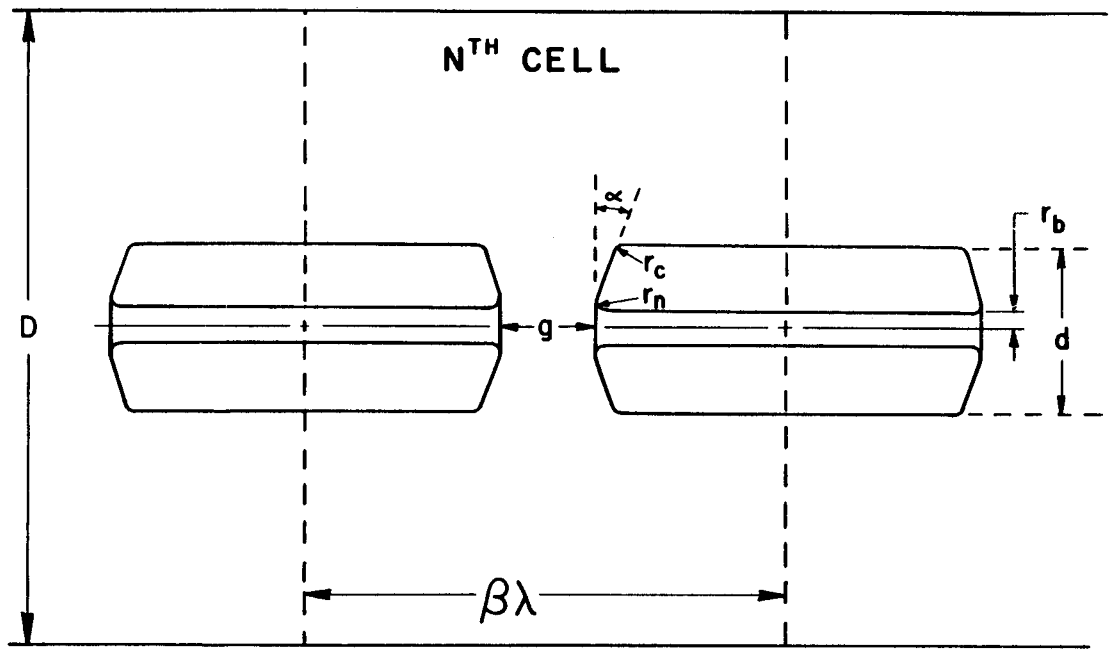

Fig. 2. **Drift Tube Linac Cell Geometry**

Table 4 - 80 MHz Drift Tube Linac Geometry - Tank 1

W(MeV)	βλ(cm)	g/βλ	D(cm)	d(cm)	r_c(cm)	r_n(cm)	r_b(cm)	α	ZT^2(MΩ/m)	10^{-3}Q	E_s/E_o
5	38.5	0.192	253	33	8.25	2.75	4.5	4°	41.4	171	6.6*
10	54.3	0.246	253	33	8.25	2.75	4.5	4°	39.8	171	5.2*
20	76.2	0.318	253	33	8.25	2.75	4.5	4°	35.1	169	4.9*

Table 5 - 80 MHz Drift Tube Linac Geometry - Tank 2

W(Mev)	βλ(cm)	g/βλ	D(cm)	d(cm)	r_c(cm)	r_n(cm)	r_b(cm)	α	ZT^2(MΩ/m)	10^{-3}Q	E_s/E_o
20	76.2	0.180	220	33	8.25	2.75	4.5	10°	35.4	127	7.3*
40	106.1	0.255	220	33	8.25	2.75	4.5	10°	32.2	123	5.9

*These entries were scaled up from the original SUPERFISH runs by a few percent to correct for finite mesh size errors in the runs.

Table 6 - 160 MHz Drift Tube Linac Geometry

W(MeV)	$\beta\lambda$(cm)	g/$\beta\lambda$	D(cm)	d(cm)	r_c(cm)	r_n(cm)	r_b(cm)	α	ZT^2(MΩ/m)	10^{-3}Q	E_s/E_o
40	53.0	0.255	110	16.5	4.125	1.375	4.5	10°	45.6	87	5.9
60	64.0	0.309	110	16.5	4.125	1.375	4.5	10°	39.3	84	5.7
80	72.8	0.350	110	16.5	4.125	1.375	4.5	10°	33.0	82	5.8
100	80.2	0.382	110	16.5	4.125	1.375	4.5	10°	28.0	81	5.9
120	86.7	0.409	110	16.5	4.125	1.375	4.5	10°	24.2	80	6.0
140	92.3	0.430	110	16.5	4.125	1.375	4.5	10°	20.9	79	6.1
160	97.4	0.449	110	16.5	4.125	1.375	4.5	10°	10.2	78	6.3
180	101.9	0.465	110	16.5	4.125	1.375	4.5	10°	16.1	77	6.3
200	106.1	0.480	110	16.5	4.125	1.375	4.5	10°	14.2	77	6.5

Table 7 - Drift Tube Linac Design Parameter Summary

	80 MHz - Tank 1	80 MHz - Tank 2	160 MHz
Frequency (MHz)	80	80	160
W_i(MeV)	5	20	40
W_f(MeV)	20	40	200
Peak Surface Field (MV/m)	17	17	23.8
E_o(MV/m)	2.585	2.347	3.66
Initial Synchronous Phase (deg)	-50	-41.5	-45
Final Synchronous Phase (deg)	-41.5	-40	-38
Bore Radius (cm)	4.5	4.5	4.5
Length (m)	10.4	12.0	84.4
Power (MW)	1.67	2.04	27.3

TABLE 8

PARMILA LISTING FOR 80 MHz DTL

```
1     parmila program        run%    1                        81/07/08. 14:17:57.

change 10 844 1 150 1
change 10 844 0 0 2
change 11 19.3  1 150 1
change 11 19.3 0 0 2
linout
1 linout subroutine no. 1     dynamical parameters
```

tank no. 1   tank length 1041.929 centimeters   18 cells   power= 1.670 mw   frequency= 80. mhz

cell number	kinetic energy	beta	length	t	tp	s	sp	quad length	quad gradient	ezero mv/m	phis	total length
0initial	5.0000	.1028						19.3000	.8440			0.000
1	5.5631	.1084	39.4641	.8587	.0421	.4049	.0522	19.3000	-.8440	2.5850	-50.0000	39.464
2	6.1595	.1140	41.6180	.8580	.0424	.4069	.0526	19.3000	.8440	2.5850	-49.5000	81.082
3	6.7922	.1197	43.7313	.8574	.0427	.4089	.0530	19.3000	-.8440	2.5850	-49.0000	124.813
4	7.4618	.1254	45.8605	.8567	.0429	.4109	.0534	19.3000	.8440	2.5850	-48.5000	170.674
5	8.1691	.1311	48.0051	.8560	.0432	.4130	.0538	19.3000	-.8440	2.5850	-48.0000	218.679
6	8.9149	.1369	50.1644	.8553	.0435	.4150	.0542	19.3000	.8440	2.5850	-47.5000	268.843
7	9.6998	.1427	52.3380	.8546	.0437	.4171	.0546	19.3000	-.8440	2.5850	-47.0000	321.181
8	10.5242	.1485	54.5246	.8537	.0441	.4196	.0551	19.3000	.8440	2.5850	-46.5000	375.706
9	11.3855	.1544	56.7172	.8495	.0453	.4261	.0557	19.3000	-.8440	2.5850	-46.0000	432.423
10	12.2839	.1602	58.9135	.8454	.0465	.4326	.0563	19.3000	.8440	2.5850	-45.5000	491.337
11	13.2196	.1661	61.1128	.8413	.0477	.4391	.0569	19.3000	-.8440	2.5850	-45.0000	552.450
12	14.1927	.1720	63.3143	.8372	.0489	.4456	.0575	19.3000	.8440	2.5850	-44.5000	615.764
13	15.2034	.1779	65.5174	.8331	.0501	.4522	.0581	19.3000	-.8440	2.5850	-44.0000	681.281
14	16.2517	.1837	67.7216	.8290	.0513	.4587	.0587	19.3000	.8440	2.5850	-43.5000	749.003
15	17.3377	.1896	69.9261	.8248	.0525	.4652	.0593	19.3000	-.8440	2.5850	-43.0000	818.929
16	18.4614	.1955	72.1304	.8207	.0537	.4718	.0599	19.3000	.8440	2.5850	-42.5000	891.059
17	19.6229	.2014	74.3338	.8166	.0549	.4783	.0605	19.3000	-.8440	2.5850	-42.0000	965.393
18	20.8221	.2072	76.5357	.8125	.0562	.4848	.0611	19.3000	.8440	2.5850	-41.5000	1041.929

1 linout subroutine no. 1   dynamical parameters

tank no. 2   tank length 1197.614 centimeters   13 cells   power= 2.042 mw   frequency= 80. mhz

cell number	kinetic energy	beta	length	t	tp	s	sp	quad length	quad gradient	ezero mv/m	phis	total length
0initial	20.8221	.2072						19.3000	.8440			1041.929
19	22.1230	.2134	78.7648	.9186	.0253	.3227	.0461	19.3000	-.8440	2.3470	-40.0000	1120.694
20	23.4562	.2195	81.0613	.9148	.0265	.3303	.0470	19.3000	.8440	2.3470	-40.0000	1201.755
21	24.8211	.2256	83.3386	.9110	.0276	.3378	.0479	19.3000	-.8440	2.3470	-40.0000	1285.094
22	26.2173	.2316	85.5969	.9072	.0287	.3453	.0488	19.3000	.8440	2.3470	-40.0000	1370.691
23	27.6440	.2375	87.8361	.9035	.0299	.3527	.0497	19.3000	-.8440	2.3470	-40.0000	1458.527
24	29.1008	.2434	90.0563	.8997	.0310	.3600	.0506	19.3000	.8440	2.3470	-40.0000	1548.583
25	30.5871	.2493	92.2573	.8961	.0321	.3673	.0515	19.3000	-.8440	2.3470	-40.0000	1640.840
26	32.1024	.2551	94.4394	.8924	.0332	.3746	.0523	19.3000	.8440	2.3470	-40.0000	1735.280
27	33.6461	.2608	96.6024	.8888	.0343	.3817	.0532	19.3000	-.8440	2.3470	-40.0000	1831.882
28	35.2177	.2665	98.7464	.8852	.0353	.3888	.0541	19.3000	.8440	2.3470	-40.0000	1930.629
29	36.8166	.2722	100.8716	.8817	.0364	.3959	.0549	19.3000	-.8440	2.3470	-40.0000	2031.500
30	38.4424	.2778	102.9778	.8781	.0375	.4028	.0558	19.3000	.8440	2.3470	-40.0000	2134.478
31	40.0946	.2833	105.0662	.8746	.0385	.4097	.0566	19.3000	-.8440	2.3470	-40.0000	2239.543

```
1
1
```

TABLE 9

PARMILA LISTING FOR 160 MHz DTL

1 parmila program run# 1 81/07/08. 15:30:52.

change 10 1022 1 150 1
change 11 26.1 1 150 1
linout
1 linout subroutine no. 1 dynamical parameters

tank no. 1 tank length 8439.792 centimeters 101 cells power= 27.338 mw frequency= 160. mhz

cell number	kinetic energy	beta	length	t	tp	s	sp	quad length	quad gradient	ezero mv/m	phis	total length
0initial	40.0000	.2830						26.1000	1.0220			0.000
1	41.2032	.2870	53.3691	.8711	.0395	.4157	.0578	26.1000	-1.0220	3.6600	-45.0000	53.369
2	42.4223	.2909	54.1614	.8671	.0407	.4215	.0577	26.1000	1.0220	3.6600	-44.6500	107.531
3	43.6597	.2949	54.8998	.8630	.0418	.4273	.0582	26.1000	-1.0220	3.6600	-44.3000	162.430
4	44.9153	.2988	55.6364	.8590	.0430	.4331	.0586	26.1000	1.0220	3.6600	-43.9500	218.067
5	46.1890	.3027	56.3712	.8550	.0441	.4388	.0591	26.1000	-1.0220	3.6600	-43.6000	274.438
6	47.4807	.3066	57.1039	.8510	.0452	.4446	.0596	26.1000	1.0220	3.6600	-43.2500	331.548
7	48.7903	.3105	57.8346	.8470	.0464	.4503	.0600	26.1000	-1.0220	3.6600	-42.9000	389.377
8	50.1177	.3144	58.5631	.8430	.0475	.4560	.0605	26.1000	1.0220	3.6600	-42.5500	447.940
9	51.4627	.3183	59.2894	.8390	.0486	.4617	.0610	26.1000	-1.0220	3.6600	-42.2000	507.229
10	52.8253	.3221	60.0134	.8351	.0497	.4674	.0614	26.1000	1.0220	3.6600	-41.8500	567.242
11	54.2052	.3260	60.7349	.8311	.0509	.4730	.0619	26.1000	-1.0220	3.6600	-41.5000	627.977
12	55.6025	.3298	61.4540	.8272	.0520	.4787	.0623	26.1000	1.0220	3.6600	-41.1500	689.431
13	57.0168	.3336	62.1705	.8233	.0531	.4843	.0628	26.1000	-1.0220	3.6600	-40.8000	751.602
14	58.4481	.3374	62.8844	.8194	.0542	.4899	.0633	26.1000	1.0220	3.6600	-40.4500	814.486
15	59.8963	.3412	63.5956	.8155	.0553	.4954	.0637	26.1000	-1.0220	3.6600	-40.1000	878.082
16	61.3610	.3450	64.3039	.8115	.0564	.5007	.0641	26.1000	1.0220	3.6600	-39.7500	942.386
17	62.8416	.3487	65.0092	.8073	.0576	.5055	.0643	26.1000	-1.0220	3.6600	-39.4000	1007.395
18	64.3380	.3525	65.7113	.8032	.0588	.5103	.0646	26.1000	1.0220	3.6600	-39.0500	1073.106
19	65.8501	.3562	66.4102	.7991	.0600	.5151	.0648	26.1000	-1.0220	3.6600	-38.7000	1139.517
20	67.3776	.3599	67.1057	.7950	.0612	.5198	.0650	26.1000	1.0220	3.6600	-38.3500	1206.622
21	68.9204	.3636	67.7980	.7909	.0624	.5245	.0653	26.1000	-1.0220	3.6600	-38.0000	1274.420
22	70.4730	.3672	68.4193	.7868	.0635	.5292	.0655	26.1000	1.0220	3.6600	-38.0000	1342.840
23	72.0331	.3708	69.0999	.7828	.0647	.5338	.0657	26.1000	-1.0220	3.6600	-38.0000	1411.939
24	73.6004	.3744	69.7738	.7788	.0659	.5384	.0660	26.1000	1.0220	3.6600	-38.0000	1481.713
25	75.1747	.3780	70.4412	.7749	.0670	.5430	.0662	26.1000	-1.0220	3.6600	-38.0000	1552.155
26	76.7557	.3815	71.1022	.7710	.0681	.5475	.0664	26.1000	1.0220	3.6600	-38.0000	1623.257
27	78.3433	.3849	71.7568	.7671	.0692	.5519	.0666	26.1000	-1.0220	3.6600	-38.0000	1695.014
28	79.9373	.3884	72.4051	.7633	.0703	.5564	.0669	26.1000	1.0220	3.6600	-38.0000	1767.419
29	81.5372	.3918	73.0471	.7594	.0714	.5605	.0670	26.1000	-1.0220	3.6600	-38.0000	1840.466
30	83.1427	.3952	73.6828	.7555	.0724	.5644	.0671	26.1000	1.0220	3.6600	-38.0000	1914.149
31	84.7536	.3985	74.3123	.7516	.0735	.5682	.0672	26.1000	-1.0220	3.6600	-38.0000	1988.461
32	86.3697	.4018	74.9357	.7478	.0745	.5720	.0673	26.1000	1.0220	3.6600	-38.0000	2063.397
33	87.9907	.4051	75.5529	.7439	.0755	.5757	.0674	26.1000	-1.0220	3.6600	-38.0000	2138.949
34	89.6166	.4084	76.1641	.7402	.0764	.5794	.0675	26.1000	1.0220	3.6600	-38.0000	2215.113
35	91.2471	.4116	76.7693	.7364	.0774	.5831	.0675	26.1000	-1.0220	3.6600	-38.0000	2291.883
36	92.8821	.4148	77.3685	.7327	.0784	.5867	.0676	26.1000	1.0220	3.6600	-38.0000	2369.251
37	94.5213	.4179	77.9620	.7290	.0793	.5903	.0677	26.1000	-1.0220	3.6600	-38.0000	2447.213
38	96.1647	.4211	78.5497	.7254	.0803	.5938	.0678	26.1000	1.0220	3.6600	-38.0000	2525.763
39	97.8120	.4241	79.1317	.7218	.0812	.5973	.0679	26.1000	-1.0220	3.6600	-38.0000	2604.895
40	99.4632	.4278	79.7081	.7182	.0822	.6008	.0679	26.1000	1.0220	3.6600	-38.0000	2684.603
41	101.1178	.4302	80.2788	.7146	.0831	.6043	.0680	26.1000	-1.0220	3.6600	-38.0000	2764.882
42	102.7741	.4332	80.8436	.7103	.0842	.6079	.0679	26.1000	1.0220	3.6600	-38.0000	2845.725
43	104.4318	.4362	81.4024	.7061	.0854	.6115	.0678	26.1000	-1.0220	3.6600	-38.0000	2927.128

TABLE 9

(CONT'D)

44	106.0907	.4391	81.9561	.7019	.0866	.6180	.0677	26.1000	1.0220	3.6600	-38.0000	[illegible]
45	107.7509	.4420	82.5019	.6977	.0876	.6186	.0678	26.1000	-1.0220	3.6600	-38.0000	[illegible]
46	109.4120	.4449	83.0430	.6936	.0887	.6219	.0676	26.1000	1.0220	3.6600	-38.0000	3174.421
47	111.0740	.4478	83.5783	.6895	.0898	.6253	.0675	26.1000	-1.0220	3.6600	-38.0000	[illegible]
48	112.7368	.4506	84.1079	.6854	.0908	.6287	.0674	26.1000	1.0220	3.6600	-38.0000	3342.314
49	114.4001	.4534	84.6319	.6815	.0919	.6321	.0673	26.1000	-1.0220	3.6600	-38.0000	[illegible]
50	116.0639	.4561	85.1505	.6775	.0929	.6354	.0672	26.1000	1.0220	3.6600	-38.0000	[illegible]
51	117.7281	.4588	85.6636	.6736	.0940	.6387	.0672	26.1000	-1.0220	3.6600	-38.0000	3597.760
52	119.3926	.4615	86.1713	.6697	.0950	.6419	.0671	26.1000	1.0220	3.6600	-38.0000	3683.821
53	121.0572	.4642	86.6738	.6659	.0960	.6451	.0670	26.1000	-1.0220	3.6600	-38.0000	[illegible]
54	122.7234	.4669	87.1714	.6627	.0968	.6474	.0668	26.1000	1.0220	3.6600	-38.0000	3857.778
55	124.3918	.4695	87.6644	.6598	.0976	.6498	.0666	26.1000	-1.0220	3.6600	-38.0000	3946.441
56	126.0604	.4721	88.1527	.6565	.0984	.6521	.0665	26.1000	1.0220	3.6600	-38.0000	4033.883
57	127.7309	.4746	88.6365	.6535	.0991	.6544	.0663	26.1000	-1.0220	3.6600	-38.0000	4122.830
58	129.4026	.4772	89.1158	.6504	.0999	.6567	.0661	26.1000	1.0220	3.6600	-38.0000	4211.348
59	131.0754	.4797	89.5906	.6474	.1006	.6589	.0660	26.1000	-1.0220	3.6600	-38.0000	4300.836
60	132.7493	.4822	90.0610	.6444	.1014	.6612	.0658	26.1000	1.0220	3.6600	-38.0000	4390.897
61	134.4241	.4847	90.5271	.6415	.1021	.6634	.0656	26.1000	-1.0220	3.6600	-38.0000	4481.524
62	136.0998	.4871	90.9888	.6385	.1029	.6656	.0655	26.1000	1.0220	3.6600	-38.0000	4572.613
63	137.7763	.4896	91.4463	.6356	.1036	.6678	.0653	26.1000	-1.0220	3.6600	-38.0000	4663.960
64	139.4534	.4920	91.8997	.6328	.1043	.6699	.0652	26.1000	1.0220	3.6600	-38.0000	4755.859
65	141.1312	.4944	92.3488	.6299	.1050	.6721	.0650	26.1000	-1.0220	3.6600	-38.0000	4848.208
66	142.8095	.4967	92.7939	.6271	.1057	.6740	.0648	26.1000	1.0220	3.6600	-38.0000	4941.002
67	144.4883	.4991	93.2350	.6243	.1064	.6759	.0646	26.1000	-1.0220	3.6600	-38.0000	5034.237
68	146.1675	.5014	93.6720	.6216	.1071	.6778	.0645	26.1000	1.0220	3.6600	-38.0000	5127.909
69	147.8470	.5037	94.1051	.6188	.1078	.6797	.0643	26.1000	-1.0220	3.6600	-38.0000	5222.014
70	149.5268	.5060	94.5344	.6161	.1085	.6816	.0641	26.1000	1.0220	3.6600	-38.0000	5316.548
71	151.2067	.5082	94.9597	.6134	.1091	.6834	.0640	26.1000	-1.0220	3.6600	-38.0000	5411.508
72	152.8868	.5105	95.3813	.6107	.1098	.6852	.0638	26.1000	1.0220	3.6600	-38.0000	5506.889
73	154.5670	.5127	95.7991	.6081	.1105	.6871	.0636	26.1000	-1.0220	3.6600	-38.0000	5602.689
74	156.2471	.5149	96.2132	.6055	.1111	.6889	.0635	26.1000	1.0220	3.6600	-38.0000	5698.902
75	157.9272	.5171	96.6236	.6029	.1118	.6906	.0633	26.1000	-1.0220	3.6600	-38.0000	5795.525
76	159.6071	.5192	97.0304	.6003	.1124	.6924	.0631	26.1000	1.0220	3.6600	-38.0000	5892.556
77	161.2866	.5214	97.4336	.5977	.1131	.6942	.0630	26.1000	-1.0220	3.6600	-38.0000	5989.989
78	162.9637	.5235	97.8328	.5943	.1139	.6961	.0627	26.1000	1.0220	3.6600	-38.0000	6087.822
79	164.6381	.5256	98.2281	.5910	.1146	.6980	.0625	26.1000	-1.0220	3.6600	-38.0000	6186.050
80	166.3100	.5277	98.6193	.5878	.1154	.6999	.0622	26.1000	1.0220	3.6600	-38.0000	6284.669
81	167.9791	.5297	99.0067	.5846	.1162	.7018	.0619	26.1000	-1.0220	3.6600	-38.0000	6383.676
82	169.6456	.5318	99.3902	.5814	.1169	.7036	.0617	26.1000	1.0220	3.6600	-38.0000	6483.066
83	171.3093	.5338	99.7698	.5782	.1177	.7065	.0614	26.1000	-1.0220	3.6600	-38.0000	6582.836
84	172.9702	.5358	100.1457	.5750	.1184	.7073	.0612	26.1000	1.0220	3.6600	-38.0000	6682.982
85	174.6283	.5378	100.5180	.5719	.1192	.7091	.0609	26.1000	-1.0220	3.6600	-38.0000	6783.500
86	176.2835	.5397	100.8865	.5689	.1199	.7109	.0607	26.1000	1.0220	3.6600	-38.0000	6884.386
87	177.9358	.5417	101.2515	.5658	.1206	.7126	.0605	26.1000	-1.0220	3.6600	-38.0000	6985.638
88	179.5852	.5436	101.6129	.5628	.1213	.7144	.0602	26.1000	1.0220	3.6600	-38.0000	7087.851
89	181.2317	.5455	101.9708	.5599	.1220	.7161	.0600	26.1000	-1.0220	3.6600	-38.0000	7189.221
90	182.8785	.5474	102.3258	.5580	.1225	.7172	.0598	26.1000	1.0220	3.6600	-38.0000	7291.547
91	184.5254	.5493	102.6780	.5561	.1229	.7183	.0596	26.1000	-1.0220	3.6600	-38.0000	7394.825
92	186.1723	.5511	103.0274	.5543	.1233	.7194	.0595	26.1000	1.0220	3.6600	-38.0000	7497.863
93	187.8194	.5530	103.3742	.5524	.1237	.7205	.0593	26.1000	-1.0220	3.6600	-38.0000	7600.827
94	189.4664	.5548	103.7184	.5506	.1241	.7216	.0591	26.1000	1.0220	3.6600	-38.0000	7704.345
95	191.1134	.5566	104.0599	.5488	.1245	.7226	.0590	26.1000	-1.0220	3.6600	-38.0000	7808.405
96	192.7604	.5584	104.3988	.5470	.1250	.7237	.0588	26.1000	1.0220	3.6600	-38.0000	7912.804
97	194.4072	.5602	104.7351	.5452	.1254	.7247	.0587	26.1000	-1.0220	3.6600	-38.0000	8017.539
98	196.0539	.5620	105.0689	.5434	.1258	.7258	.0585	26.1000	1.0220	3.6600	-38.0000	8122.808
99	197.7005	.5637	105.4001	.5417	.1262	.7268	.0583	26.1000	-1.0220	3.6600	-38.0000	8228.008
100	199.3469	.5655	105.7288	.5399	.1266	.7279	.0582	26.1000	1.0220	3.6600	-38.0000	8333.737
101	200.9931	.5672	106.0551	.5382	.1270	.7289	.0580	26.1000	-1.0220	3.6600	-38.0000	8439.798

to determine the input beam characterization for a PARMILA run in the 80 MHz linac. We assume that by a suitable perturbation of the RFQ vanes, the output transverse beam ellipse can be brought into a matched configuration for the 80 MHz drift tube linac, with very little change in the longitudinal phase space. We have assumed that the longitudinal phase space configuration at the input to the 80 MHz drift tube linac is the same as for the 90 percent contour at the output to the RFQ. The outer 10 percent of the beam from the RFQ is neglected in this procedure. In our overall transmission estimate through the accelerator we have conservatively assumed that this outer 10 percent is lost. After having generated the new random particles, a second run with PARMILA was made to simulate the performance through the 80 MHz drift tube linac to 40 MeV. Then in the same way, using the output beam characteristics from the 80 MHz run to determine input beam characteristics for 160 MHz linac, PARMILA was used in a third run to simulate the performance through the 160 MHz linac and to give the final output beam characteristiics.

Figure 3 shows beam profiles for 360 particles in the RFQ. The upper profile gives the horizontal displacement, x, versus cell number. The dotted lines show the position of the vanes in the horizontal plane. The middle profile gives phase relative to the synchronous particle phase, and the lower profile gives energy relative to the synchronous particle energy. Dotted lines on the lower two profiles show the separatrix boundaries for zero beam current.

The lower left corner of Fig. 4 shows longitudinal phase space at the output of the RFQ. The separatrix at zero beam current is also shown in dotted lines. Above and to the right of this plot are the projected histograms on the phase and energy axes respectively. In the upper right corner is a plot of y versus x which shows the beam spot at the exit of the RFQ.

Figures 5 and 6 show the corresponding plots for the 80 MHz linac. Figures 7 and 8 show the corresponding plots for the 160 MHz linac. In particular, Fig. 6 corresponds to the beam configuration at 40 MeV and Fig. 8 gives the final beam configuration at 200 MeV.

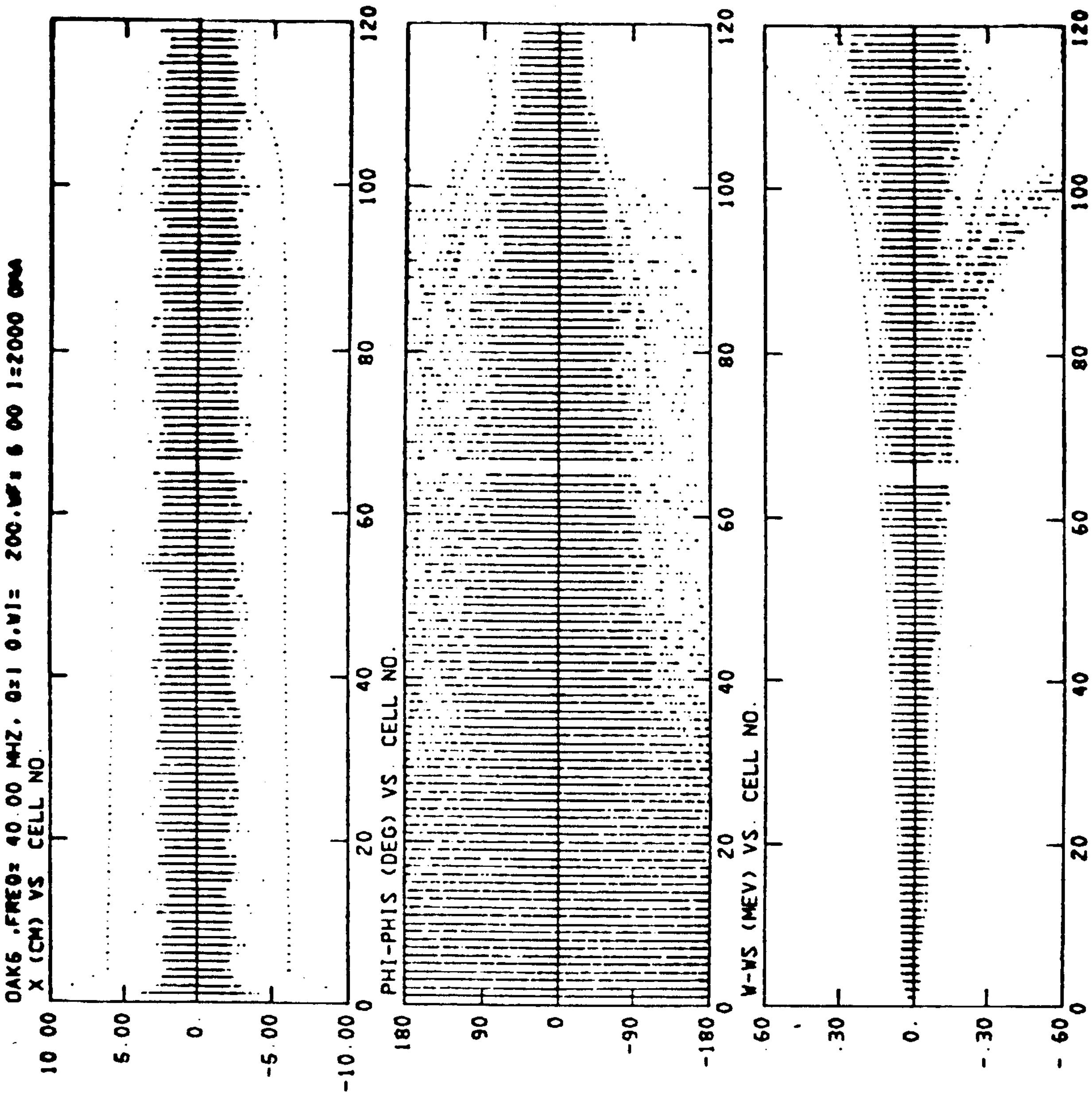

FIG. 3

RFQ BEAM PROFILES

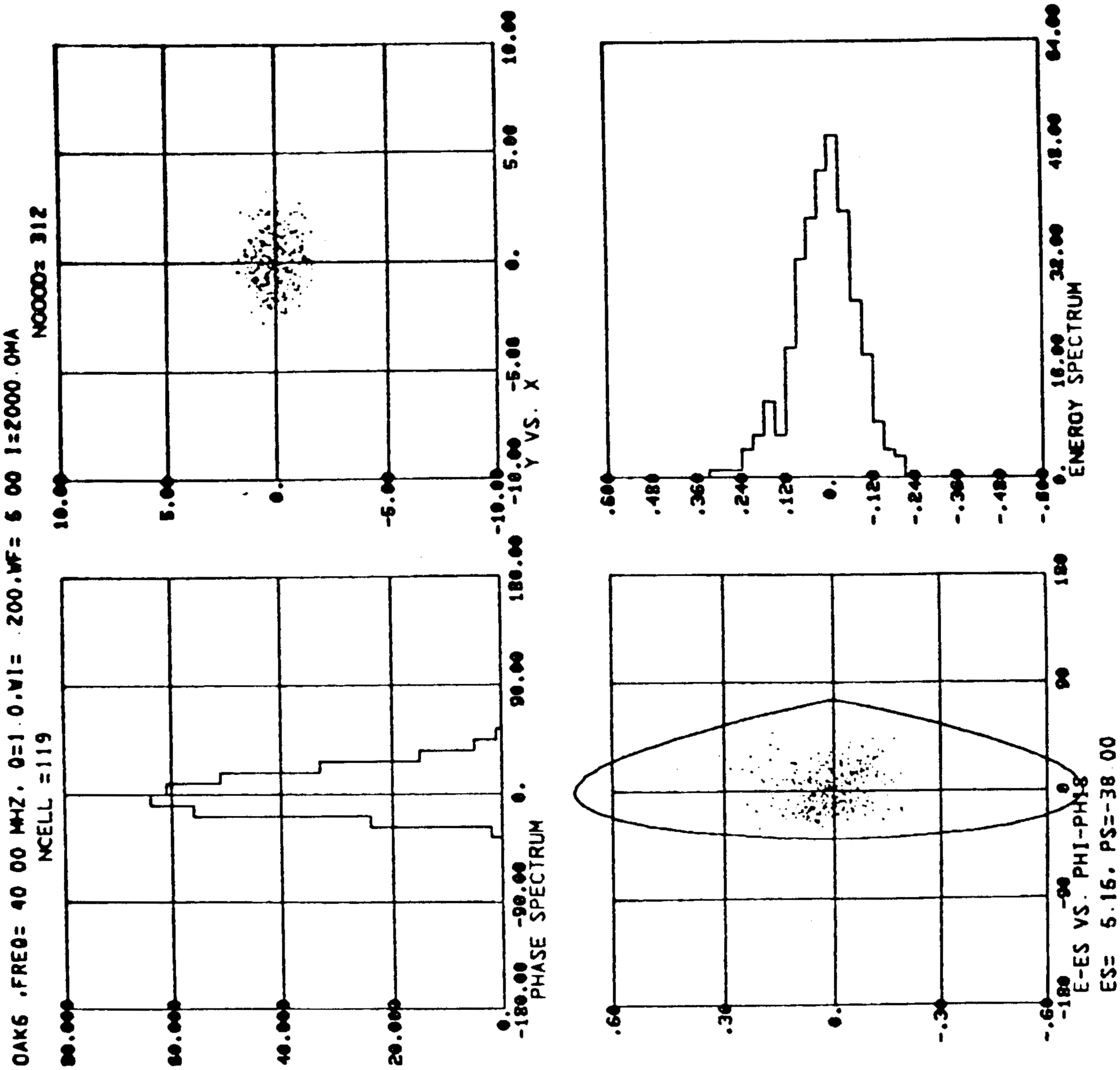

FIG. 4

RFQ FINAL PHASE SPACE

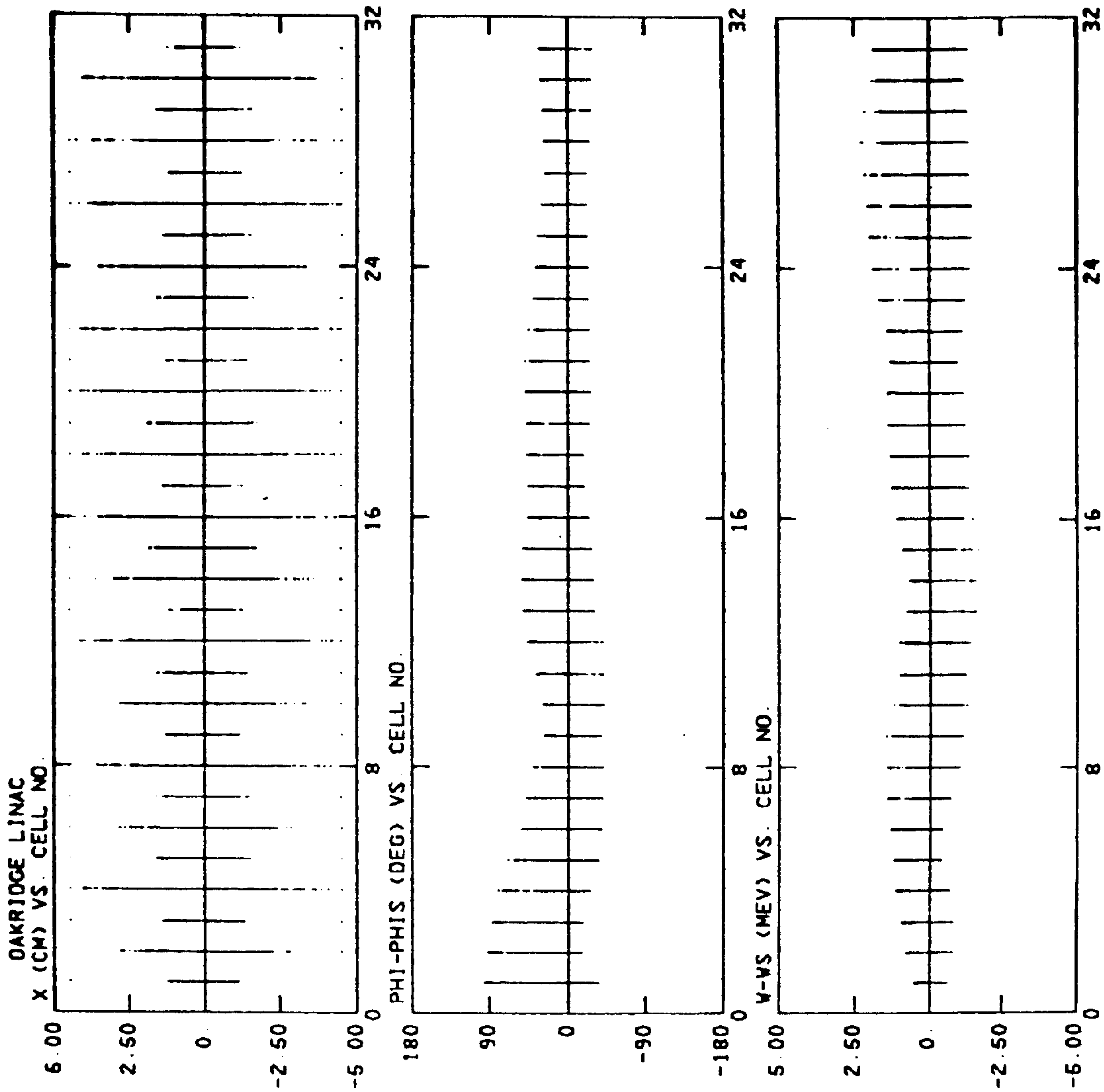

FIG. 5.

80 MHz DTL BEAM PROFILES

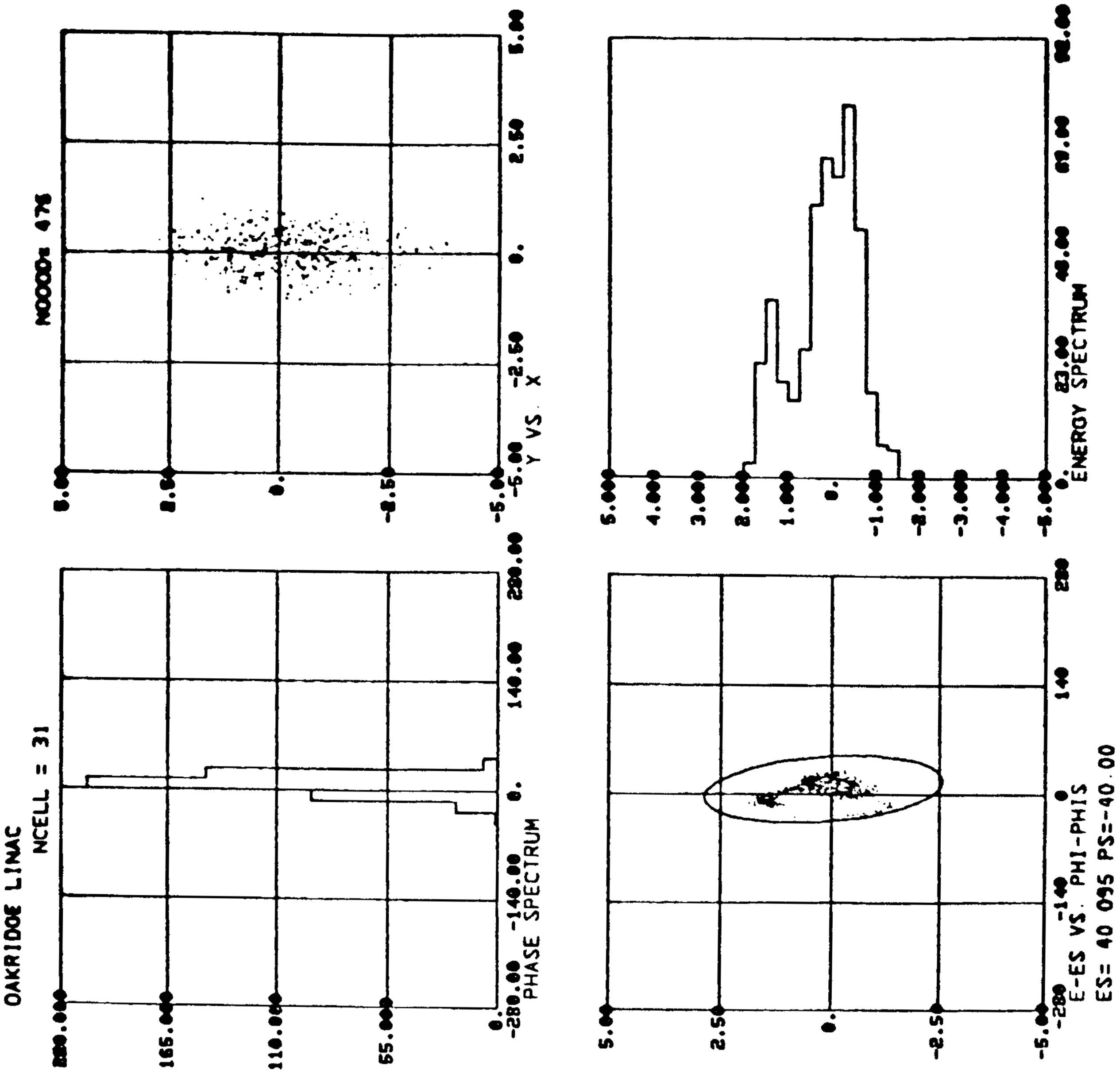

FIG. 6.

80 MHz DTL FINAL PHASE SPACE

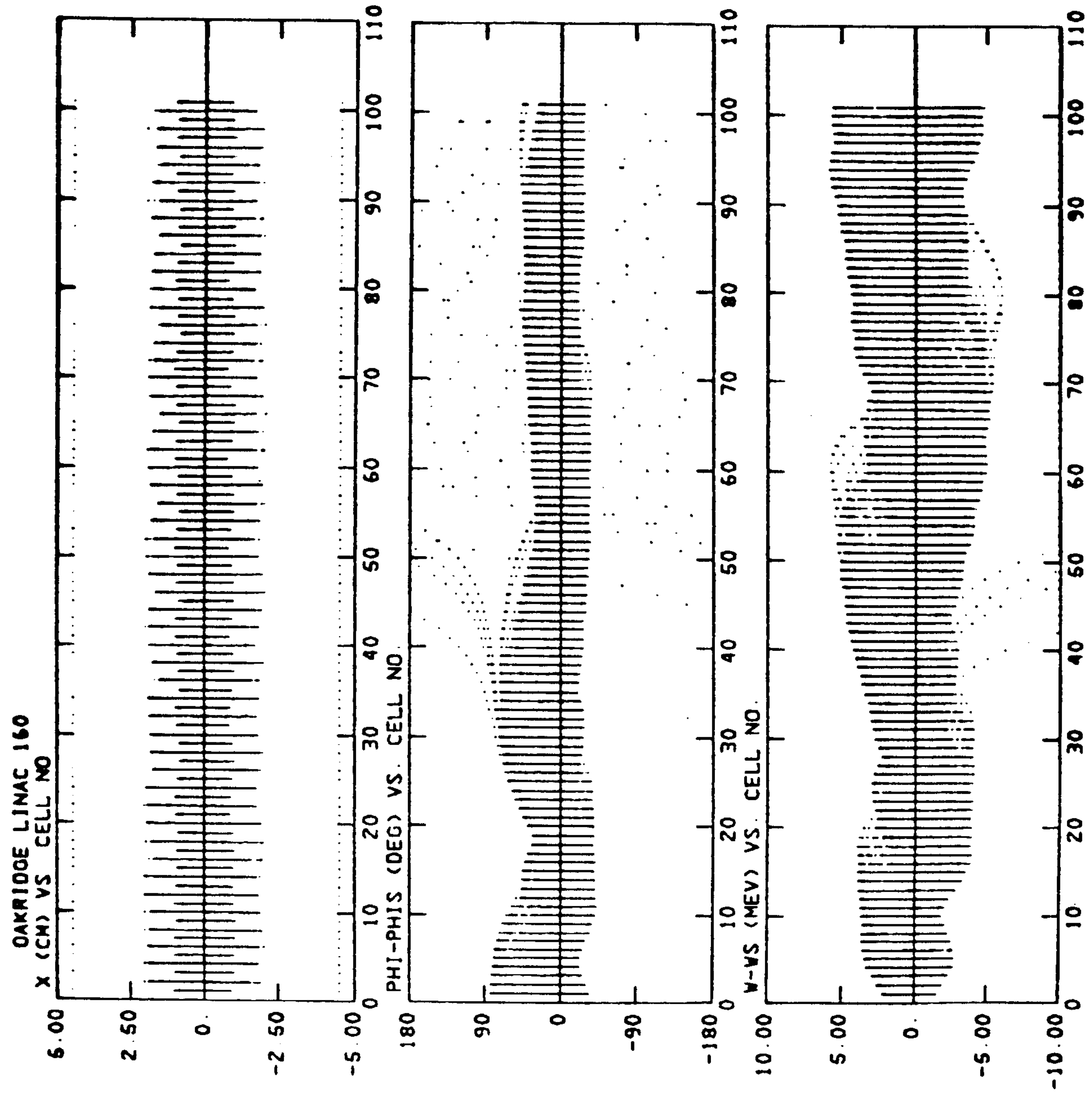

FIG. 7.

160 MHz DTL BEAM PROFILES

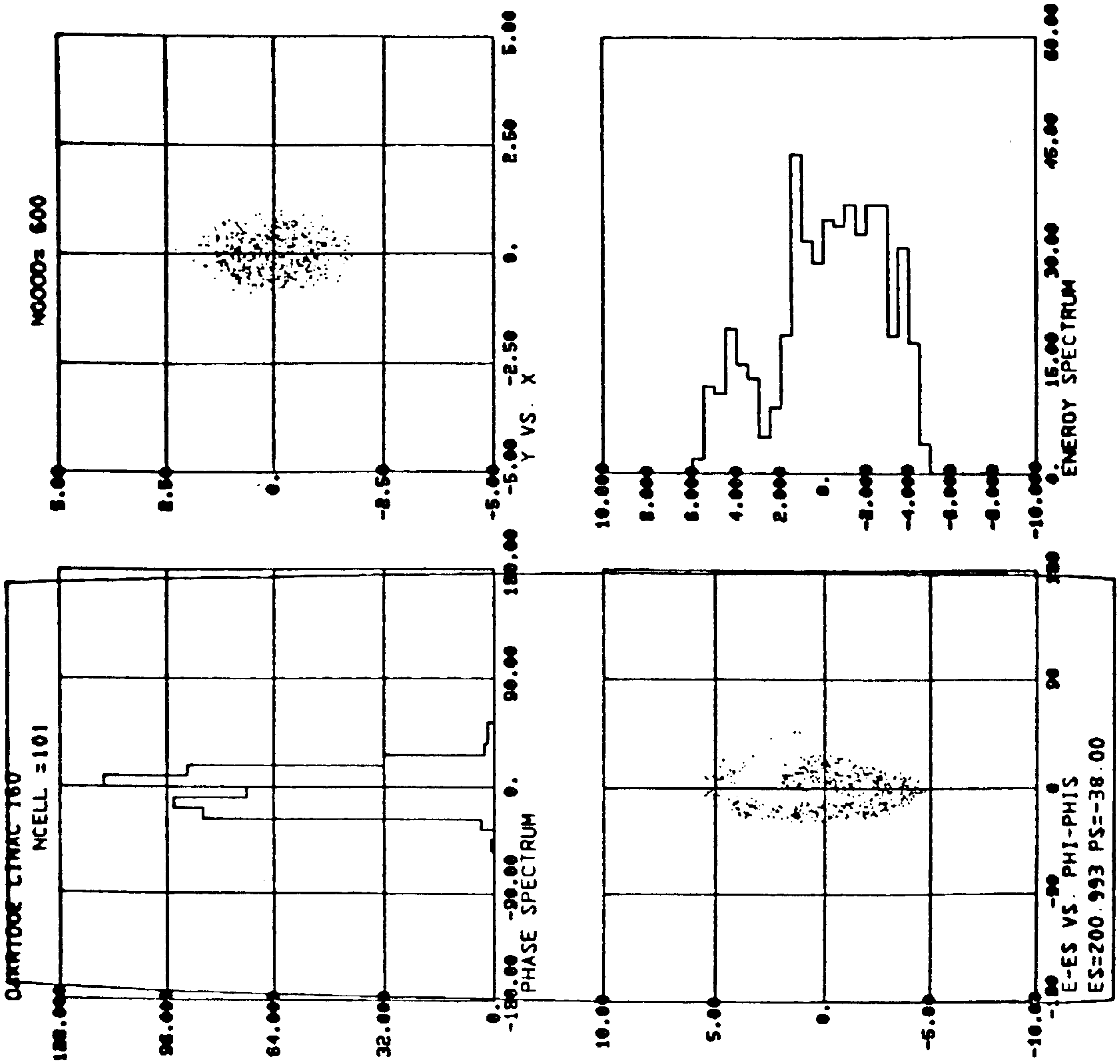

FIG. 8.

160 MHz DTL FINAL PHASE SPACE

Table 10 gives the transmission for the RFQ and the two drift tube linacs as obtained from PARMTEQ and PARMILA. We will use these numbers to obtain the number of particles in the output beam micropulse. First, as was discussed earlier, we multiply the transmission numbers for the two drift tube linacs by 90 percent to correct for the outer 10 percent of the particles not correctly included in the simulation procedure. Then, if we assume 3.1×10^{11} protons per bunch at the input to the RFQ (2A peak current) we obtain 2×10^{11} protons per bunch at 200 MeV.

The full width output beam characteristics at 200 MeV for the 90 percent contour are listed in Table 11. The output beam time spread is about 1 ns and the transverse beam size is about 1 inch. If the target could be placed directly at the 200 MeV output, the beam requirements on target, that were stated in the introduction, would be satisfied.

Table 10

Linac Transmissions

	T
RFQ	87 %
80 MHz DTL	95 %
160 MHz DTL	99 %

Table 11

Estimated Full Width Output Beam Characteristics at 90 Percent Contour

ΔW-(MeV)	10
$\Delta\phi$ (deg)	54
Δt (ns)	0.94
Δx (cm)	1.5
Δy (cm)	3.0
ϵ_n(cm-mr)	4.5π

VIII. RF Power Requirements

If the beam is to be pulsed at 1 kHz, we would like to pulse the rf power at the same rate. In the previous sections we have listed the peak rf power for the RFQ (Table 2) and the drift tube linacs (Table 7). These power levels correspond to the cavity dissipation values at the operating field levels. During the time that the cavities are being filled with rf power, it is necessary to provide additional overdrive power in order to bring the cavity excitation levels to their full operating values within a finite fill time t_f. After the cavities are fully excited, the rf power source can continue to supply only the cavity losses for the short time that the beam pulse is injected and accelerated. After the beam bunch has been accelerated, the rf drive can be switched off and the cavity excitation levels will decay exponentially. It is desirable to have a short fill time in order to minimize rf power dissipation in the cavities during the filling time, provided that the excess overdrive power needed is not too large. We use the following formula to calculate fill time.

$$t_f = \frac{Q_0}{\pi f K} \quad \frac{1}{1+\beta} \quad \ln\left[\frac{1}{1-\left(\frac{P_{cu}}{P_{cu}+P_{od}}\right)^{1/2}}\right] \qquad (1)$$

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where the fill time, t_f, is the actual time for the field to go from zero to the design value, f is the rf frequency, Q_o is the calculated Q value for an ideal copper surface and an ideal cavity (with no stems for a drift tube linac), β is the matching parameter for the rf drive line into the cavity, P_{cu} is the peak cavity power dissipation at the design excitation and P_{od} is the overdrive power (used only while filling the cavity). The parameter K is used to correct the ideal Q for resistivity degradation of realistic copper surfaces and for the effect of stems in drift tubes. We use K = 1.15 for the RFQ and K = 1.3 for a drift tube linac.

As the overdrive power level is increased, the fill time is reduced, but at the expense of increasing the overall power requirement. As β is increased from the matched value of 1, the resulting over-coupling decreases the fill time, but at the expense of wasted reflected power. Thus, fill time can be reduced, but at the expense of increased available peak rf power. It is, of course, desirable to reduce the fill time to reduce the average rf power dissipation. We have not done a detailed cost optimization for this problem, but have chosen the solution, given in Table 12, which appears reasonable to us, and which we think should not be too far from an optimum solution. The Q listed in Table 12 is an average over the values given in tables, 4, 5, and 6. We have chosen to substantially overcouple the rf drive to the 80 MHz linac by making β = 4. The total peak rf power required, P_{gen}, includes copper power P_{cu}, overdrive power P_{od} and reflected power for the mismatched cases. The resulting fill times, t_f, were calculated from equation 1. The duty factor at a 1 kHz rate and the resulting average power P_{ave} values are also listed.

We have tried to estimate the effect of beam loading, by calculating the energy gained in the accelerator cavities by a single beam bunch, and by comparing this energy gain with the stored energy in that cavity. The resulting energy gain to stored energy ratios are at most a few tenths of a percent, which suggests that beam loading can be ignored.

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Table 12

RF Power Requirements

	$10^{-3}Q_o$	P_{cu}(MW)	P_{od}(MW)	β	R_{gen}(MW)	t_f(ms)	Duty (%)	P_{ave}(MW)
RFQ	34.3	5.4	5.4	1	10.8	0.146	14.6	1.58
80 MHZ DTL - Tank 1	170.5	1.67	1.67	4	5.22	0.145	14.5	0.76
80 MHz DTL - Tank 2	124.9	2.04	2.04	4	6.38	0.106	10.6	0.68
160 MHz DTL	80.5	27.3	27.3	1	54.6	0.086	8.6	4.66

IX. Cost Estimate

We base our approximate cost estimates on formulas, developed at Los Alamos, using the materials and fabrication costs only of several ion linacs. For the RFQ structure cost we use

$$C_s = \frac{2.55}{\sqrt{f(\text{MHz})}} \ \text{M\$/m} \quad . \tag{2}$$

For an Alvarez drift tube linac we use

$$C_s = \frac{2.27}{\sqrt{f(\text{MHz})}} \ \text{M\$/m} \quad . \tag{3}$$

For rf power equipment we have used cost figures based on the average power. We use 2.0 M$/MW at 40 MHz, 2.5 M$/MW at 80 MHz and 3.0 M$/MW at 160 MHz. We use the lengths given in Tables 2 and 7 and the average rf power value from Table 12 to obtain structure costs and rf power equipment costs. The results are presented in Table 13.

The total structure cost is 26.7 M$. The total rf cost is 20.7 M$. The total cost for structures plus rf is 47.4 M$.

We have not included the costs of the ion source, the ion source development, the beam chopper, the low energy beam transport line and the higher energy beam transport line, if one is necessary. Also, we have not included physics, engineering, and testing costs.

Table 13

Cost Estimate

	Structure (M$)	RF (M$)	Total M($)
RFQ	5.81	3.16	8.97
Alvarez 1	2.64	1.90	4.54
Alvarez 2	3.05	1.70	4.75
Alvarez 3	15.15	13.98	29.13

X. Summary and Conclusions

As can be seen in Section VII, the design presented in this report was successful in meeting the main goals that were stated in the Introduction, except for the output beam intensity, which was 2×10^{11} protons per bunch from our computer simulations. It is our feeling that, based on what is known at present about beam current limits in rf linacs, it will be difficult to increase this to 5×10^{11} protons per bunch without greatly increasing the size and cost.

The linac cost as estimated in Section IX, together with the development required for an appropriate pulsed ion source, suggests that alternative ideas should be carefully evaluated to see how they compare. For example, one such suggestion would be to consider a high frequency linac, such as was developed for the PIGMI project at Los Alamos to accelerate lower beam currents of H^- to 200 MeV for injection into an accumulator ring, where high intensity bunches could be accumulated for subsequent fast extraction onto a target.

There are some basic reasons why this linac design lead to a high cost. In order to provide for adequate peak beam current capability, it is necessary to operate the linacs at relatively low frequency. This allows for the necessary large aperture. However, low frequency operation implies lower shunt impedance and longer linac structures. Also, low frequency operation implies larger structure diameters. For both reasons the low frequency structures will be expected to cost more. In addition, the large low frequency structures have a larger Q, which implies a larger fill time. Since the cavities must be filled for every single beam pulse in the scheme evaluated here, more power is required per beam pulse than in a more conventional mode, where the rf is turned on in macropulses, and where many micropulses are accelerated per macropulse. Thus, if a way is found so that a higher frequency linac can be used, and if the beam can be accelerated in the more conventional mode of a string of micropulses within a given rf macropulse, the cost can be expected to reduce significantly.

XI. Acknowledgements

We are grateful to Rene Mills, who helped us get a version of PARMILA on the CDC 7600, and to Robert Hamm who suggested the use of the duopigatron ion source.

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