Assessment Of Alternative RF Linac Structures For APT

Phase 1 Effort, Final Report

Performed by:
Advanced Technology & Development Center
Northrop Grumman Corporation
Bethpage, NY

For:
Program Office, Accelerator Production Of Tritium
Los Alamos National Laboratory
Los Alamos, NM

26 March, 1997

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University Of California Contract Number D69700016-8Y

Study Participants*

- David Berwald, Principal Investigator
- Al Burger, Manufacturing Planning
- Tim Myers, Accelerator Cost Estimation
- Carl Paulson, Linac Physics Modeling
- Michael Peacock, Accelerator System Modeling
- Edward Peterson, Manufacturing Planning
- Chris Piaszczyk, RAM Modeling
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Table Of Contents Summary

This report provides the results of this assessment. It is organized as follows:

A detailed Table of contents is provided below. Additional outputs developed from this study effort have been incorporated into the APT Conceptual Design Report, which is currently in preparation.

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1.0 Introduction And Background

The APT program has been examining both normal and superconducting variants of the APT linac for the past two years. A decision on which of the two will be the selected technology will depend upon several considerations including the results of ongoing feasibility experiments, the performance and overall attractiveness of each of the design concepts, and an assessment of the system-level features of both alternatives. The primary objective of the *Assessment Of Alternative RF Linac Structures For APT* study reported herein was to assess and compare, at the system-level, the performance, capital and life cycle costs, reliability/availability/ maintainability (RAM) and manufacturing schedules of APT RF linear accelerators based upon both superconducting and normal conducting technologies. A secondary objective was to perform trade studies to explore opportunities for system optimization, technology substitution and alternative growth pathways and to identify sensitivities to design uncertainties.

The effort was organized as three tasks, defined on the following pages, which were performed for Los Alamos by Northrop Grumman's Advanced Technology & Development Center during the period August, 1996 - January, 1997. A primary vehicle used for performing this assessment was the relatively new Accelerator Systems Model (ASM), a Fortran computer code which has been jointly developed by Northrop Grumman, G. H. Gillespie Associates and Los Alamos over the past four years.

1.1 Task 1 Statement Of Work: Baseline Cases

<u>Task 1 Statement Of Work</u>:

Northrop Grumman shall review Los Alamos-supplied point design concepts for both the normal conducting and superconducting APT accelerators and shall update ASM computer models based upon these configurations. These models shall encompass the overall APT plant, with emphasis on the APT accelerator. They shall encompass all aspects of the APT accelerator layout and performance (including RAM characteristics) and shall include the costs associated with all accelerator structures, the RF power system, and associated support services, buildings and construction services. Subject to Los Alamos approval, these ASM models and computer-generated results shall become baselines for the remainder of this subcontract activity.

1.2 Task 2 Statement Of Work: Trade Studies

<u>Task 2 Statement Of Work</u>:

The baseline normal and superconducting APT accelerator designs will each reflect a specific set of technologies, performance parameters and constraints. These may or may not be optimal, depending upon the specific criteria to be used for design selection. For example, Table 1 depicts several possibilities for parametric optimization of APT accelerator designs. In collaboration with Los Alamos, Northrop Grumman shall review, prioritize, select and perform ASM trade studies optimization issues, within the limits of available resources. Each study shall encompass the same level of detail and features as the baseline described in Task 1.

Table 1 - Some Trade Study Areas For Optimization Of The APT Linac

- ***Normal vs. Superconducting Structures***
- Other Alternative Accelerating Structures
- ***Beam Energy vs. Current***
- ***Accelerating Field Gradient***
- Transition Energies & Matching Conditions
- ***RF Coupler Power Transmission***
- RF Frequency Selection (High Energy Linac)
- ***RF Amplifier Technology***
- ***RF Tanking***
- High Voltage Power Technology
- ***Current Funneling***
- Multiple vs. Single Beamlines
- ***RF Amplifier Redundancies***
- RF Pre-Amplifier Staging
- ***Multiple vs. Single Ion Injectors***
- ***Other RAM Trades & Sensitivities***
- Design Optimization vs. Expected Plant Life
- ***Part Time Or Part Year Operation***

[Note: Studies related to the topics shown in *bold italics* above were performed as part of the Task 2 effort.. A more complete and precise listing of the trades performed is provided in Section 4 of this report.]

1.3 Task 3 Statement Of Work: Manufacturing Schedule Evaluation

Task 3 Statement Of Work:

Northrop Grumman shall review existing manufacturing studies and plans (to be provided by Los Alamos), to provide an independent assessment of such existing APT manufacturing process flows and schedules for the baseline normal conducting and superconducting APT accelerators. These flows and schedules shall include all aspects of procurement, manufacturing, fabrication, testing and integration of the APT accelerator structures and rf power systems. Possibilities for improvement in areas involving manufacturing producability, cost, and scheduling shall be identified.

2.0 Executive Summary

This Executive Summary is comprised of the *APT Cost And RAM* presentation given at the JASONs Review of the APT Program on 21 January, 1977. The presentation materials provided herein are augmented by the addition of descriptive facing page text.. In addition, a brief discussion of the results of Task 3, Manufacturing Schedule Evaluation, is provided.

The reader should note that the contents of this section were selected to provide a reasonably succinct and self-contained representation of the important results of the study rather than a complete record of the methods, approach and results. The later are contained in the balance of the report, beginning with Section 3.1 which discusses the ability of the Accelerator Systems Model (ASM), which was used to model the APT linacs, to match the specific APT point design configurations.

2.1 The Accelerator Systems Model (ASM)

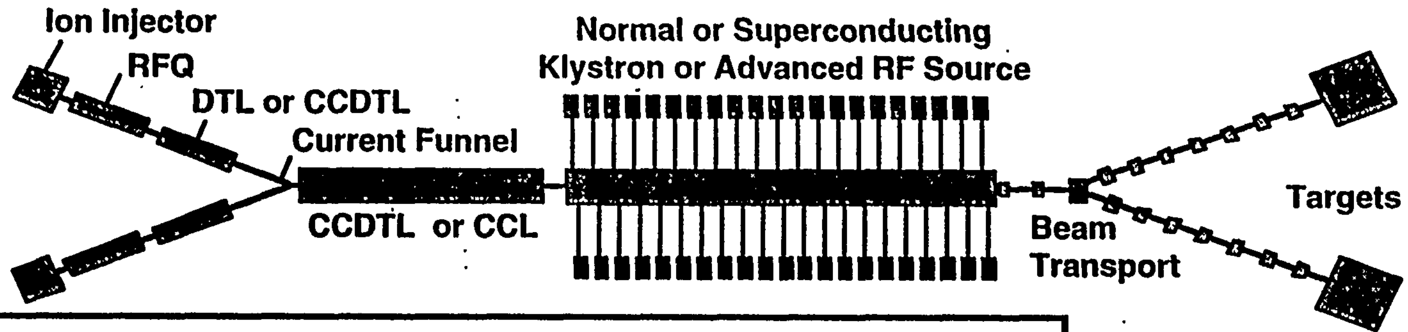
The Accelerator Systems Model (ASM), developed by Northrop Grumman in cooperation with G. H. Gillespie Associates and Los Alamos during the past four years, was used extensively in the performance of Tasks 1 and 2 of the *Assessment Of Alternative RF Linac Structures For APT* study, the results of which are summarized in this section. ASM provides the following unique capabilities for detailed layout and system-level evaluation of advanced rf linacs:

- Ability to model ion linac configurations based upon a large number of existing and recently proposed normal and superconducting linac structures, operating over a wide range of rf frequencies
- Detailed cell-by-cell tracking of the linac configuration and the electrical and rf power system performance
- Generation of detailed component inventory that includes all accelerator systems and dedicated facilities
- System reliability, availability, maintainability (RAM) modeling for estimation of operational availability and the cost of component replacement and/or refurbishment
- Cost analysis capability which encompasses capital, construction, and annual operating costs, resulting in a single life cycle cost estimate

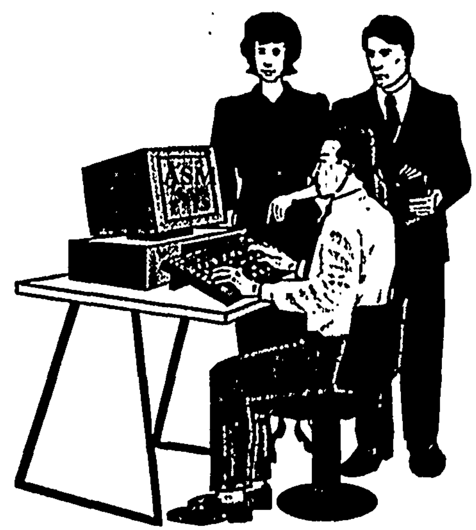
As indicated on the following two charts, the current version of ASM, includes specific models for all of the accelerating structures in the APT designs, allowing the analyst to consider many linac configurations and technology trades using a consistent set of modeling algorithms.

The on-going ASM development effort is currently concentrating on the improvement of existing models (e.g., diagnostics, instrumentation and control and cryogenics), implementation of an automated capability for parameter trades, and adaptation of the code for pulsed ion linacs. Future ASM variants dedicated to applications involving electron beam accelerators, free electron lasers, ion cyclotrons and ion storage rings are envisaged.

Accelerator Systems Model (ASM*) Used To Perform Study



Existing Models:	
• Ion Sources	- ECR or RF-Driven
• LEBTs	- PMQ or EMS
• RFQ's	- Conv. or Resonantly Coupled
• Matching	- Interstructure & Funnel
• DTL	- Various Lattices & Magnet Types
• CCDTL	- 2 or 3 Gaps
• CCL	- Individual Tanks or RF Supermodule
• SCL	- Low β Independent Cavities or High β Multi-Elliptical Cell Cavities
• HEBT	- Per User Specified Layout
• RF Power	- Complete Station Incl. Output/Driver Tubes, Power Supplies, Transport
• Services	- Thermal (Incl. , Cryoplant), Elec., I&C
• Dedicated Facilities	- Tunnel, Buildings
• Cost	- Life Cycle Incl. Labor, Materials, Learning Curves, Elec., Staff, Replacements, etc.
• RAM	- Requirements Allocation & Sensitivities



* ASM is a joint development of Northrop Grumman, G.H. Gillespie Assoc., and Los Alamos

ASM Calculational Flow

Inputs
- Global requirements (energy, current, freq., mass, charge)
- Linac RF structures & config.
- Physics recipes
- RF power tech. & config.
- Engineering, RAM, cost data
- Energy break points/other logic

Beamline Physics Layout
- Injector & RFQ sizing & performance
- Matching between accelerating structures
- Cell-by-cell lattice & magnet requirements
- Cell-by-cell electric field ramping & power consumption
- Tanking break points
- Beamline power & parts inventory buildup

RF Power Sizing
- Selection & sizing of 2-3 stage RF amplifier chain
- RF configuration (AC line to accelerator cavity)
- Determination of AC power requirements

RAMI Estimation
- Equipment failure rates & times to repair or replace
- Subsystem reliability/availability/ maintainability (RAM) buildups (including spares)
- System reliability & availability estimation

Accelerator / RF System Cost
- Non-recurring engineering cost
- Unit manufacturing costs for major components & assemblies
- Scaling for size & quantity
- Building & facility costs
- Operating costs (staff, elec., replacements
- Discounted present value of life cycle cos

Summary
- Cell & tank details
- Accelerator layout
- RF & power flow
- Reliability & availability
- Capital & operating costs
- Manufacturing Schedule
- Life cycle costs

2.2 APT Linac Cost Summary

ASM cost estimates for APT plants based upon the baseline normal conducting and superconducting APT accelerators discussed are summarized in this section. The relative capital, operating and life-cycle costs of these two technology alternatives, for nominal tritium production levels of 2.2 and 3.15 kg/yr are provided. Trade studies which investigate possibilities for cost savings at the lower of the two production levels are also summarized.

The development of the estimates reported herein was preceded by an activity which compared our ASM results for the cost of the APT accelerator with an earlier Los Alamos cost estimate (LA-UR-95-4045) for a smaller superconducting linac (100 mA, 1000 MeV). [This analysis is provided as Appendix B.] Of special note, the ASM total capital cost estimate was within 14% of the previous Los Alamos estimate.

Highlights Of Cost Estimation Approach

Highlights of the cost estimating approach are provided in the next two charts. The "overnight capital cost" is comprised of all of the sum of the plant equipment, labor and materials costs from Preliminary Design through completion of the 1.5 year startup phase, but without consideration of escalation or other financing considerations during the life of the construction project. The overnight cost is added to a discounted sum of the operating costs over a 40 year period to establish the estimated life cycle cost (details of discounting assumptions will be provided later in this section). All costs in this section (and throughout this document) are referenced to 1995 dollars.

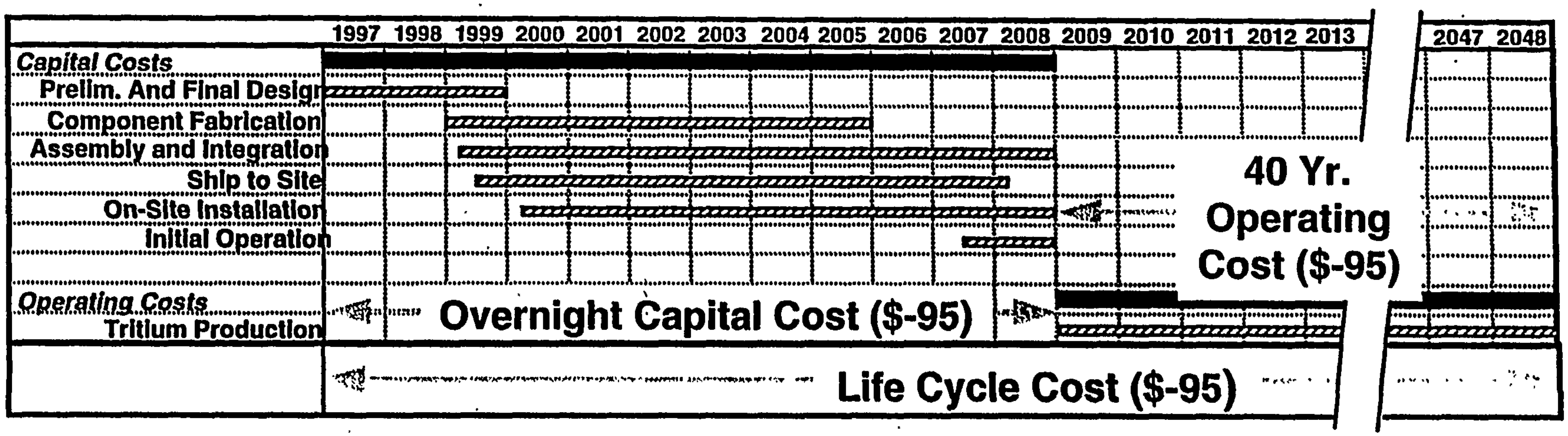
The capital cost estimates were developed, in priority order, from scaled actual costs of as-built hardware, vendor-supplied cost estimates and grass roots estimates which considered the costs and/or labor associated with all of the aspects of design, engineering, procurement, manufacturing and test.. Where multiple procurements of the same item were involved, learning curve scaling was used to reflect the reduced unit costs. For example, if the learning curve is 94% and the normalized cost of the first unit or lot is 1.0, then the cost of the second unit or lot is 0.94 and the cost of the fourth unit is 0.88, the cost of the eighth unit is 0.83, the cost of the sixteenth unit is 0.78, etc.

The operating costs are dominated by the cost of electricity, assumed to be 34.5 mil/kWeHr (0.0345 $/kWeHr) during the first year of operation and the cost of component replacement and refurbishment. The later cost is strongly influenced by the failure rate analysis which is embedded in the RAM analysis (see Section 2.3).

The cost analysis assumes that much of the equipment will be furnished by the government to the integrating contractor. Only the first few (Typ. 10) units would be purchased by the contractor. The net effect is to eliminate multiple procurement burdens in the procurement cycle.

The equipment budget for the linac includes contingency, which varies according to the subsystem to be procured. The analysis reported herein assumes an average contingency of 21%.

Highlights Of Cost Estimation Approach



- Capital costs developed from:
  - Scaling from similar hardware programs (e.g., RFQ)
  - Vendor cost data (e.g., superconducting cavities, RF power station)
  - Grass roots estimates and manufacturing plans (e.g., CCDTL)
  - Learning curve savings for multiple lots and rate production
- Operating costs developed from:
  - Electricity consumption (34.5 mil/kWeHr)
  - Plant staff ($73,000 per FTE)
  - Component replacement (or refurbishment) costs
- Extensive use of Government Furnished Equipment:
  - RF power equipment, vacuum pumps, focusing magnets, copper
- Average contingency = 21%

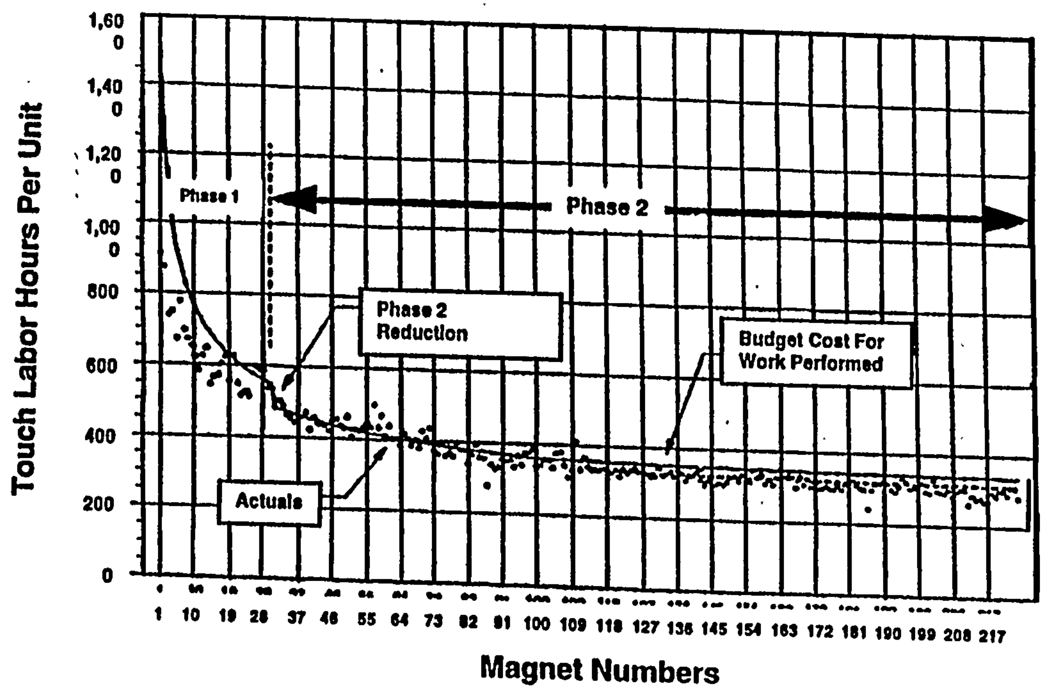
Typical Rate Production Learning Curve

The next chart indicates typical "learning experience" in the production of high precision superconducting equipment (i.e., Northrop Grumman's production of the superconducting dipole magnets for Brookhaven's Relativistic Heavy Ion Collider, RHIC). The best fit to this experience is a 91% learning curve, which was used to estimate the production costs for the linac accelerator structures, both superconducting and normal conducting. A less aggressive 94% learning curve was used to estimate the rf power system components. The estimates all assume that manufacturing engineering inputs to the design process occur beginning during Preliminary Design (cost of this activity included in the estimates) and that there will be one large production run (one manufacturer) for each major component. If the production is to be split among more than one manufacturer, then the cost will increase because the learning curve savings will be substantially reduced.

Typical Rate Production Learning Curve

- "Learning curve" equations have been used to capture reduction in estimated unit cost for large production runs
  - 94% LC for rf power systems
  - 91% LC for linac structures
- Assumptions used for APT linac:
  - Single supplier to maximize benefit (duplicate production lines will progress through same learning curve)
  - Manufacturing engineering involvement beginning during preliminary and final design phase

Example: RHIC Superconducting Dipole Magnet Production Program



- 256 design changes prior to high rate production
- Touch labor range: 900 - 250 Hr (360 Ave.)
- Results in 91% learning curve

Cost Estimate For SCL Cryomodule - Basis Of Estimate

The following two charts illustrate the cost basis incorporated into ASM for the APT superconducting cryomodules. As indicated, vendor cost estimates were obtained and evaluated for nearly all of the major components that comprise the cryomodule. The exception was the rf drive line, for which a vendor estimate was not available. The cost of the drive line was separated into four components. Cost estimates for two of these, the vacuum window and the rf coupler, were developed in-house.

As indicated, our estimate for the total cost of the cryomodules, based upon a single manufacturer and a 91% learning curve is $151 M [If multiple suppliers will be required, an upwards cost adjustment will be required to reflect lower learning curve savings and additional management oversight]. The partitioning of the cost among the major components indicates that the cavities, drive lines and cryostat/cryogen distribution system each represent about about 30% of the cost and that the superconducting quadrupole magnets represent about 10% of the cryomodule cost. The average unit costs of the various cryomodule components (after learning curve savings) are shown on the right hand column of the second chart.

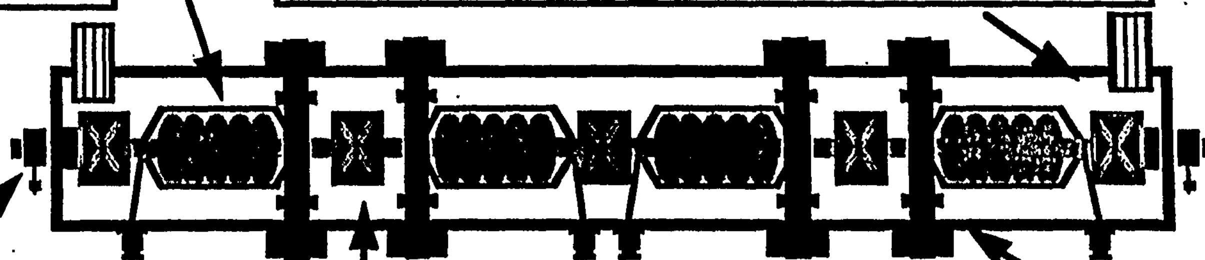
Cost Estimate For SCL Cryomodule - Basis Of Estimate

Accelerating Cavity Assembly
- Five accelerating cells
- De-tuner assembly
- Surrounding cryogen vessel and all flanges

Basis of Estimate:
- Vendor quotes for completed assemblies
- In-house estimate for installation labor

Cryostat & Cryogen Distribution System
- Stainless steel vessel
- Cryogen piping, valves and flanges

Basis of Estimate:
- Vendor quote for steel and "catalog" cryogenic equipment
- In-house labor estimate for fabrication of cryostat and integration of cryogen distribution equip.



Miscellaneous Parts & Final Assembly Labor
- Beam tube and flanges
- External support structure
- Flanges and other parts

Basis of Estimate:
- Vendor estimates for equipment
- In-house estimate for labor

Superconducting Focusing Magnet
- Magnet
- Power Supply
- Alignment Mechanism

Basis of Estimate:
- Vendor quote for equipment
- In-house estimate for installation labor

RF Drive Line
- 2 m section of drive line (2 m)
- Turbo pump (50 l/s)
- Vacuum window
- Cryogenically cooled rf coupler

Basis of Estimate:
- Vendor quote for "catalog" RF and vacuum equipment,
- In-house estimate for window cost
- In-house estimates for fabrication and integration labor

Cost Estimate For SCL Cryomodule - Cost Breakdown

Summary :

	Average cost ($K-95)
Medium β cryomodule (3 cavities):	$1,186
High β cryomodule (4 cavities):	$1,421

Details :

	Qty.	Costs ($M-95) Labor	Material	Total	% Total	Average Cost ($k)
Final Design Mods/Production Support	1 lot	$1.6	$0.0	$2	1%	$1640
5-Cell Niobium Cavities and Cryogen Vessel	409	$12.3	$29.5	$42	28%	$102
Cryostat and Cryogen Distribution System	110	$9.8	$34.8	$45	30%	$405
Cylindrical Window	818	$0.0	$21.3	$21	14%	$26
Stub RF Drive Line	818	$1.6	$20.8	$22	15%	$27
Superconducting Magnets and P.S.	519	$1.0	$12.7	$14	9%	$26
Integration, Installation and C/O	110	$5.4	$0.0	$5	4%	$49
	Totals:	$31.6	$119.0	$151	100%	

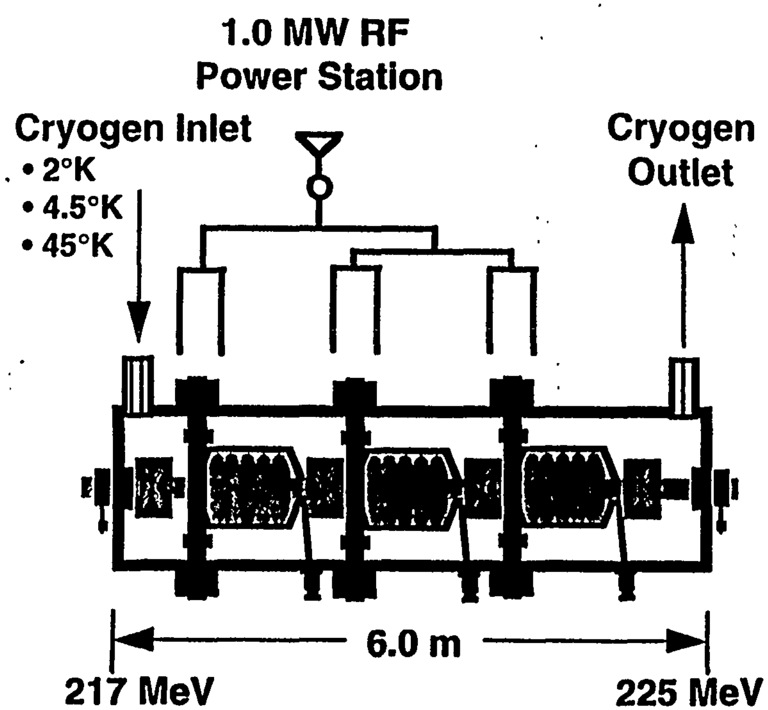
Accelerator Production of Tritium

Relative Complexity Of Normal And Superconducting Linac Structures

The following chart illustrates the relative complexity of equivalent sections of the APT superconducting and normal conducting linac (SCL and NCL) designs, each of which would accelerate the beam from 217 MeV to about 226 MeV. As shown, the functional equivalent of one superconducting cryomodule (comprised of three 5 cell cavities, four superconducting quadrupole magnets and associated other components) is a section of coupled cavity linac comprised of 7 flanged segments and 7 bridge couplers requiring 49 precision machined cells in 7 sizes. The results of our manufacturing studies, which consider all of the manufacturing and tuning/test operations required to produce both types of equipment, indicate that the additional complexity associated with the CCL (e.g., 27 furnace brazes per segment) leads to a 15% higher overall cost for this structure, despite its lower design energy (1300 MeV for NCL vs 1780 MeV for SCL).

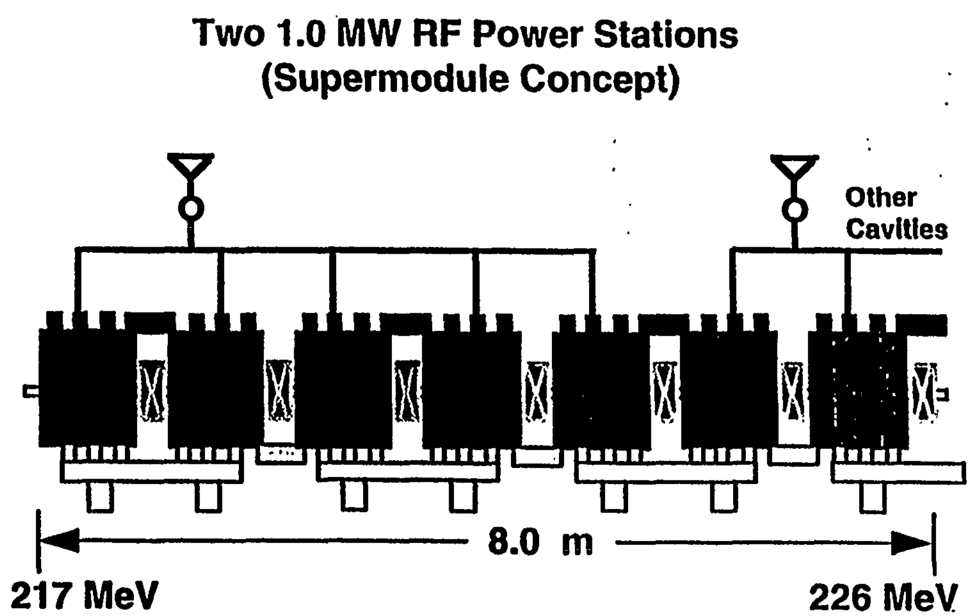
Relative Complexity Of Normal And Superconducting Linac Structures

Med. β Cryomodule #1



SCL Cryomodule Details:
- 1 cryomodule assembly
- 15 identical cells (123 e-beam welds)
- 4 superconducting EMQs
- 6 50 l/s turbo pumps (in RF coupler)
- 3 cryogen loops

Comparable CCL Section



CCL Section Details:
- 7 flanged segments and bridge couplers
- 49 cells in 7 sizes (189 furnace brazes)
- 7 room temperature EMQs
- 7 500 l/s ion pumps
- 7 water loops (not shown in sketch)

Superconducting & Normal Conducting Linac Capital Costs

(~ 3 kg/yr Production Level)

The following chart summarizes and compares the estimated capital costs of superconducting and normal conducting linacs, each sized to produce approximately 3 kg/yr of tritium. The superconducting linac (SCL) is the 100 mA, 1780 MeV accelerator described to the JASONS, more fully described in the APT Conceptual Design Report (draft). The normal conducting linac (NCL) is the 136 mA, 1300 MeV baseline with a current funnel at 20 MeV. [The lower current SCL is a single beamline without current funneling.]

As shown, the NCL capital cost is estimated to exceed that of the SCL by 25%. One key cost driver for the NCL is an ~40% greater requirement for rf power (due to increased power dissipation in the accelerator structure as well as the allocation of spare rf stations for the supermodule configuration). The greater complexity of the NCL linac structure (discussed earlier) leads to an ~15% cost increase in the estimated cost of the linac structure and associated support systems. Including its 16 kW cryoplant, the cost of thermal control for the SCL is considerably more expensive than for the water cooling systems required for the NCL.

Superconducting & Normal Conducting Linac Capital Costs

(~ 3 kg/yr Production Level)

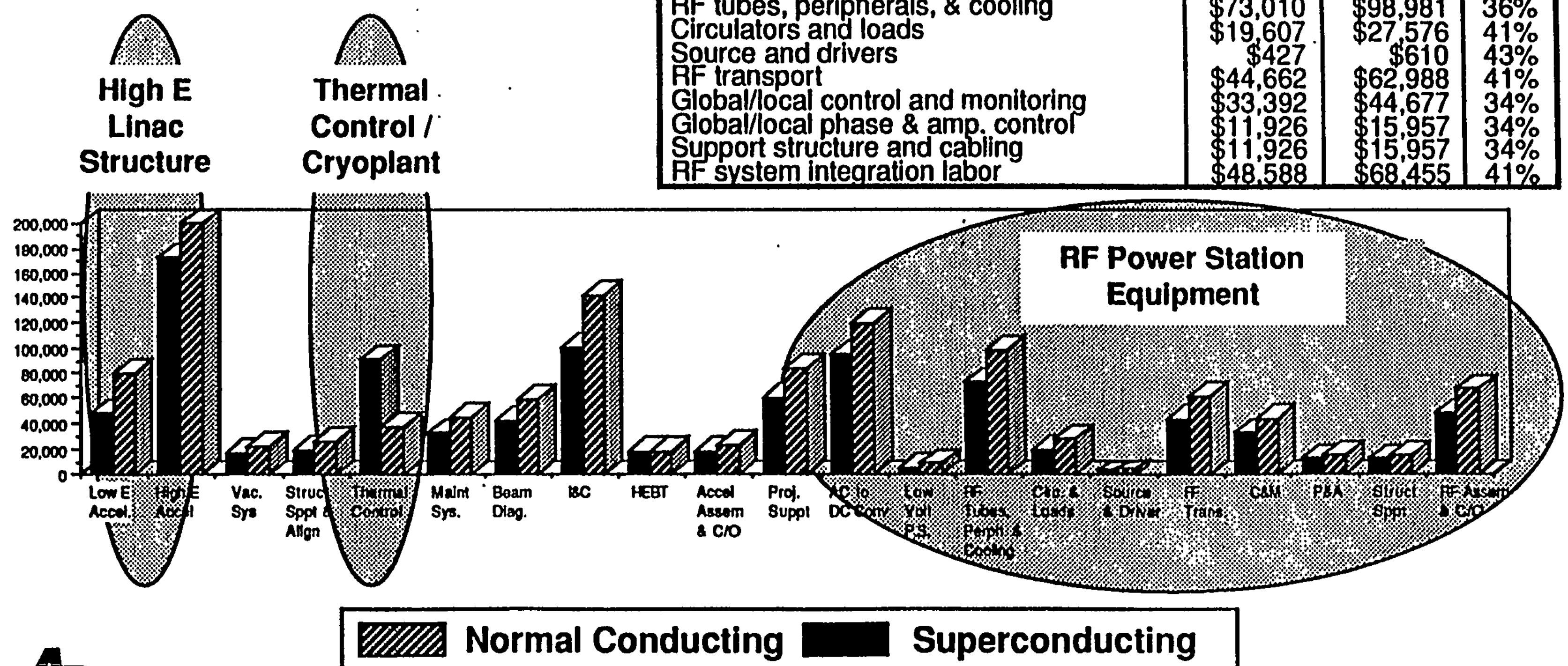
Total Cost Before Contingency

Superconducting: $983 M

Normal Conducting: $1,230 M

Delta: 25%

Capital Cost Categories	SCL	NCL	Δ%
Low energy accelerator	$49,755	$80,335	61%
High E Accel (100 MeV - final energy)	$173,972	$199,786	15%
Vacuum systems	$16,791	$23,825	42%
Structural support & alignment	$19,563	$27,394	40%
Thermal control	$92,663	$39,777	-57%
Maintenance systems	$34,149	$47,618	39%
Beam diagnostics	$43,004	$60,726	41%
Instrumentation & control	$106,243	$152,762	44%
HEBT	$18,125	$18,125	0%
Accelerator assembly and C/O	$19,734	$26,208	33%
Project support	$64,608	$88,849	38%
AC to DC conversion and distribution	$95,232	$121,138	27%
Low voltage power supplies	$5,573	$7,834	41%
RF tubes, peripherals, & cooling	$73,010	$98,981	36%
Circulators and loads	$19,607	$27,576	41%
Source and drivers	$427	$610	43%
RF transport	$44,662	$62,988	41%
Global/local control and monitoring	$33,392	$44,677	34%
Global/local phase & amp. control	$11,926	$15,957	34%
Support structure and cabling	$11,926	$15,957	34%
RF system integration labor	$48,588	$68,455	41%



Superconducting & Normal Conducting Linac Life Cycle Costs

(~ 3 kg/yr Production Level)

The following chart summarizes and compares the estimated life cycle costs of superconducting and normal conducting linacs, each operated with a nominal plant availability of 75%, which has been used for the financial comparison (unless otherwise noted). With 75% availability the SCL and NCL would produce 3.15 kg/yr and 2.90 kg/yr, respectively.

As indicated, the overnight cost is added to a discounted sum of the operating costs over a 40 year period to establish the estimated life cycle cost (LCD). The "overnight capital cost" is comprised of all of the sum of the plant equipment, labor and materials costs from Preliminary Design through completion of the 1.5 year startup phase, but without consideration of escalation or other financing considerations during the life of the construction project. The contribution due to the operating cost is decreased by 3.8% for each year of operation. [This corresponds to an annual escalation of 3.8 %/yr discounted by a 7.7 %/yr cost of money (i.e., 1.038 / 1.077 = 1 / 1.038), equivalent to a real cost of money of 3.8%.] The net effect is to reduce the impact of the annual operating cost by the factor 20.4/40, representing a 49% decrease.

The results indicate that the life cycle costs of the NCL are estimated to be 20% higher than those of the SCL. The capital cost component of the life cycle cost of the overall SCL-based APT plant is estimated to be 37%. The electricity cost is the second largest contributor, 34%. The cost of replacing and/or refurbishing linac components (primarily the rf power equipment) is estimated to require 18% of the life cycle cost.

Superconducting & Normal Conducting Linac Life Cycle Costs

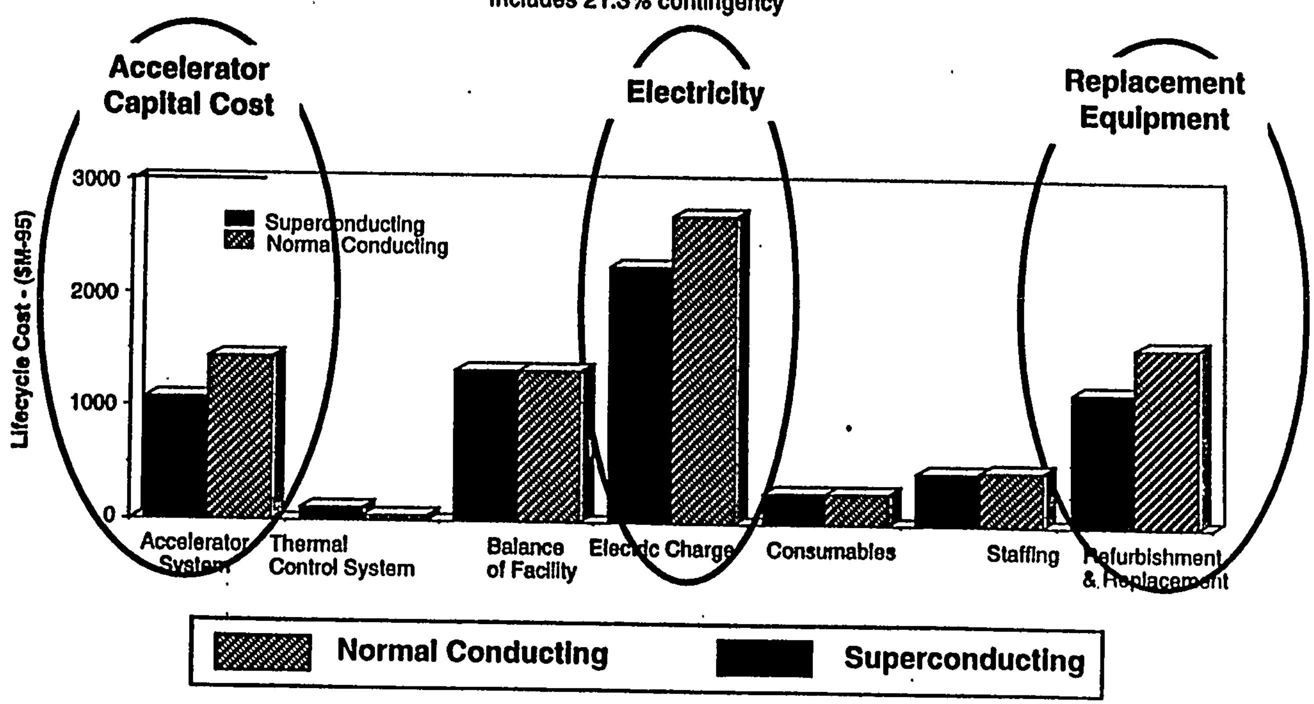
(~ 3 kg/yr Production Level)

$$\text{Life Cycle Cost} = \text{Total Overnight Cost} + \sum_{n=1}^{40} \frac{O\&M_n}{(1.038)^n}$$

$$= \text{Total Overnight Cost} + 20.4 \times O\&M_1$$

	SCL	NCL	Delta
Overnight Cost Components:			
Accelerator System*	1,192	1,492	300
Balance of Facility	1,334	1,334	------
O&M Cost Components:			
Electric Charge	2,274	2,910	636
Accel Electric Usage (MWe)	*425*	*559*	*134*
Consumables	282	282	------
Staffing	469	473	4
Refurbishment & Replacement	1,189	1,587	398
Total Life Cycle Cost:	6,740	8,078	1,338 (20%)

* Includes 21.3% contingency



Marginal Cost Per Unit Of Tritium Production

(~ 3 kg/yr Production Level)

The results of a study to determine the "marginal cost of tritium production", defined as the cost to change the production capability by a small amount about the nominal capability, are shown on the next chart. Both the marginal capital cost and the marginal life cycle cost for the linac (only) were calculated. The marginal life cycle cost is relevant to an increase or decrease in the tritium requirement while the marginal capital cost can also be relevant to a situation in which it is desirable to build-in additional reserve (e.g., as a hedge against lower than expected system availability) while not necessarily expecting to produce a different (higher or lower) quantity of tritium.

The approach was to consider an additional cryomodule (and the associated costs incl. rf power, support services, building/tunnel extension) to produce an additional 16.8 MeV of energy and an additional 0.033 kg/yr of tritium (1.05%). The marginal linac capital cost ratio, defined as the capital cost per unit of tritium production at the margin divided by the average capital cost per unit of tritium production, was estimated to be 46%. The marginal linac life cycle cost ratio, similarly defined, was estimated to be 54%. Although the corresponding quantities have not been estimated for the overall APT plant, the expectation is that both ratios will decrease significantly because much of the the balance of facility (target/blanket and balance of plant) cost is independent of small changes in the linac.

These results indicate that increases in production about the current SCL design point can be highly cost effective, but that the benefit for producing less tritium with this design is diminished by the same ratio.

Marginal Cost Per Unit Of Tritium Production

(~ 3 kg/yr Production Level)

<u>Trade Study Objective</u>:

- Evaluate cost of small increase in linac energy and breeding rate

<u>Major Considerations</u>:

- Consider addition of one high β cryomodule, two rf stations and other costs for additional 16.8 MeV
- Calculate added linac capital and life cycle cost, added tritium breeding capability

<u>Conclusions</u>:

- Marginal linac <u>capital cost ratio</u> is 46%of average cost per unit production.
- Marginal linac <u>life cycle cost ratio</u> is 54% of average.
- Most of T/B and BOP cost is fixed, so expect overall plant to have lower (than above) cost sensitivity to tritium production level

Baseline Final Energy	1780 MeV
Energy Increment	16.8 MeV
Baseline T Prod. (@ 75%)	3.15 kg/yr
Tritium Prod. Increment	.033 kg/yr (1.05%)
Baseline Linac Capital Cost	1182 $M
Linac Capital Cost Increment	5.7 $M
Marginal Linac Capital Cost Ratio	5.4 $M/% T Prod.
Baseline Linac Life Cycle Cost	4616 $M
Linac Life Cycle Cost Increment	26 $M
Marginal Linac Life Cycle Cost Ratio	25 $M/% T Prod.

Superconducting & Normal Conducting Linac Capital Costs

(~ 2 kg/yr Production Level)

The following chart summarizes and compares the estimated capital costs of superconducting and normal conducting linacs, each sized to produce approximately 2.2 kg/yr of tritium. The superconducting linac (SCL) is the 100 mA, 1780 MeV accelerator described to the JASONS (same as earlier). The normal conducting linac (NCL) is a 100 mA, 1300 MeV configuration that does not include a current funnel at 20 MeV.

As shown, the NCL capital cost is estimated to exceed that of the SCL by 11% (despite the fact that the SCL is capable of the higher production level). One key cost driver for the NCL is an ~10% greater requirement for rf power. Again, the greater complexity of the NCL linac structure (discussed earlier) leads to an ~15% cost increase in the estimated cost of the linac structure and associated support systems.

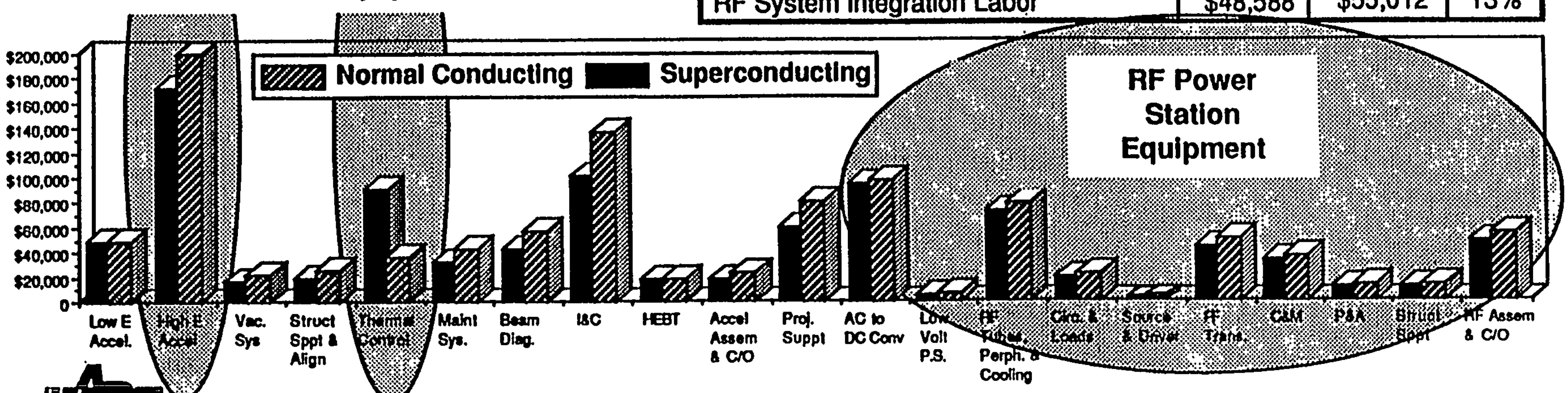
Superconducting & Normal Conducting Linac Capital Costs

(~ 2 kg/yr Production Level)

- *Total Cost Before Contingency*
- *Superconducting*: $982,949*
- *Normal Conducting:$1,086,665*
- *Delta: 11%*

* Superconducting machine capable of 3.15 kg/yr production by increase of coupler power from 140 kW to 210 kW

Capital Cost Categories	SCL	NCL	Δ%
Low Energy Accelerator	$49,755	$49,755	0%
High E Accel (100 MeV to Final Energy)	$173,972	$199,786	15%
Vacuum Systems	$16,791	$22,298	33%
Structural Support & Alignment	$19,563	$25,980	33%
Thermal Control	$92,663	$38,430	-59%
Maintenance Systems	$34,149	$45,192	32%
Beam Diagnostics	$43,004	$57,864	35%
Instrumentation & Control	$106,243	$144,174	36%
HEBT	$18,125	$18,125	0%
Accelerator Assembly and C/O	$19,734	$26,208	33%
Project Support	$64,608	$85,049	32%
AC to DC Conversion and Distribution	$95,232	$97,560	2%
Low Voltage Power Supplies	$5,573	$6,324	13%
RF Tubes, Peripherals, & Cooling	$73,010	$79,767	9%
Circulators and Loads	$19,607	$22,240	13%
Source and Drivers	$427	$486	14%
RF Transport	$44,662	$50,713	14%
Global/Local Control and Monitoring	$33,392	$35,993	8%
Global/Local Phase & Amplitude Control	$11,926	$12,855	8%
Support Structure and Cabling	$11,926	$12,855	8%
RF System Integration Labor	$48,588	$55,012	13%



Summary Of Superconducting Vs Normal Conducting Costs

The following chart summarizes and compares the estimated capital and operating costs, life cycle costs, and unit tritium production costs for APT plants based upon the normal and superconducting linac technologies at the lower (about 2 kg/yr) and higher (about 3 kg/yr) production levels. The capital, operating costs and life cycle costs are shown for the linac alone and for the entire APT plant (including the balance of facilities).

The unit tritium production costs are calculated according to two methods. The first method assumes that the plant availability in all cases will be a nominal 75%. This method decouples the economic assessment from the RAM assessment, which depends upon numerous independent assumptions (described in the next subsection). The second method factors in the results of the estimated plant availability based upon our RAM analysis.

Several observations are of interest. First, the NCL operating at the lower production level is estimated to have a higher capital, operating and life cycle cost than the SCL operating at the higher production level. This is reflected in the unit cost of tritium, which is over 50% higher for the NCL operating at the lower production level. If both machines are compared at the higher production level, the NCL has a unit cost that is over 30% higher. If both machines are compared at the lower production level, the NCL has a unit cost that is 13-18% higher.

Summary Of Superconducting Vs Normal Conducting Costs

	Lower Production Level			Higher Production Level		
Linac Alone	SCL*	NCL	Δ (%)	SCL	NCL	Δ (%)
• Capital Cost ($M)	1192	1318	11	1192	1492	25
• Annual Operating Cost ($M/yr)	142	164	16	157	207	32
• Life Cycle Cost ($M)	4089	4664	14	4395	5715	30
APT Plant						
• Capital Cost ($M)	2526	2652	5	2526	2826	12
• Annual Operating Cost ($M/yr)	192	215	12	207	257	24
• Life Cycle Cost ($M)	6443	7036	9	6749	8078	20
Unit Tritium Production Costs						
• Beam Energy (MeV) / Current (mA)	1340/100	1300/100		1780/100	1300/136	
• Instantaneous Tritium Production Rate (kg/yr)	2.93	2.84		4.20	3.86	
• Tritium Production @75% Plant Availability (kg/yr)	2.20	2.13		3.15	2.90	
• Normalized Tritium Production Cost @75% Plant Availability	2.93	3.30	13	2.14	2.79	30
• Plant Avail. Predicted By RAM Model (%)	71.4	67.7**		71.4	67.7	
• Tritium Prod. @ Plant Avail. Predicted By RAM Model (kg/yr)	2.09	1.92**		3.00	2.61	
• Norm. Tritium Prod. Cost @Plant Avail. Predicted By RAM Model	3.08	3.66**	18**	2.25	3.10	38

* Superconducting machine capable of higher production level by increase of coupler power from 140 kW to 210 kW

** Plant availability assumed to be same as calculated for higher production level. This is conservative because configuration has no beam funnel and requires ~55 fewer rf power stations in the high energy linac. Therefore calculated unit costs will be in the high side.

Life Cycle Cost Versus Cost Of Electricity

The following chart summarizes the impact of the cost of electricity during the first year of operation on the life cycle cost (LCC) of APT plants based upon the normal and superconducting linacs at both production levels, assuming an average plant capacity factor of 75%. [Referring to earlier discussion, the reader is reminded that our LCC definition assumes that the cost of electricity will escalate by 3.8%/yr over the lifetime of the plant and that the discounted value of the electricity charge averages 51% of the first year charge.]

Comparing the values at the high end of the scale (50 mil/kWeH) to those at the low end of the scale
(20 mil/kWeH), the LCC sensitivity to the cost of electricity is between 1.8 and 2.4 $B (depending upon which if the four cases) or about 35%. As the baseline value, 34.5 mil/kWeH is somewhat arbitrary and subject to change as the local and national electric power industries evolve, this input should be reevaluated on a regular basis. Opportunities to benefit from off-peak rates should also be considered.

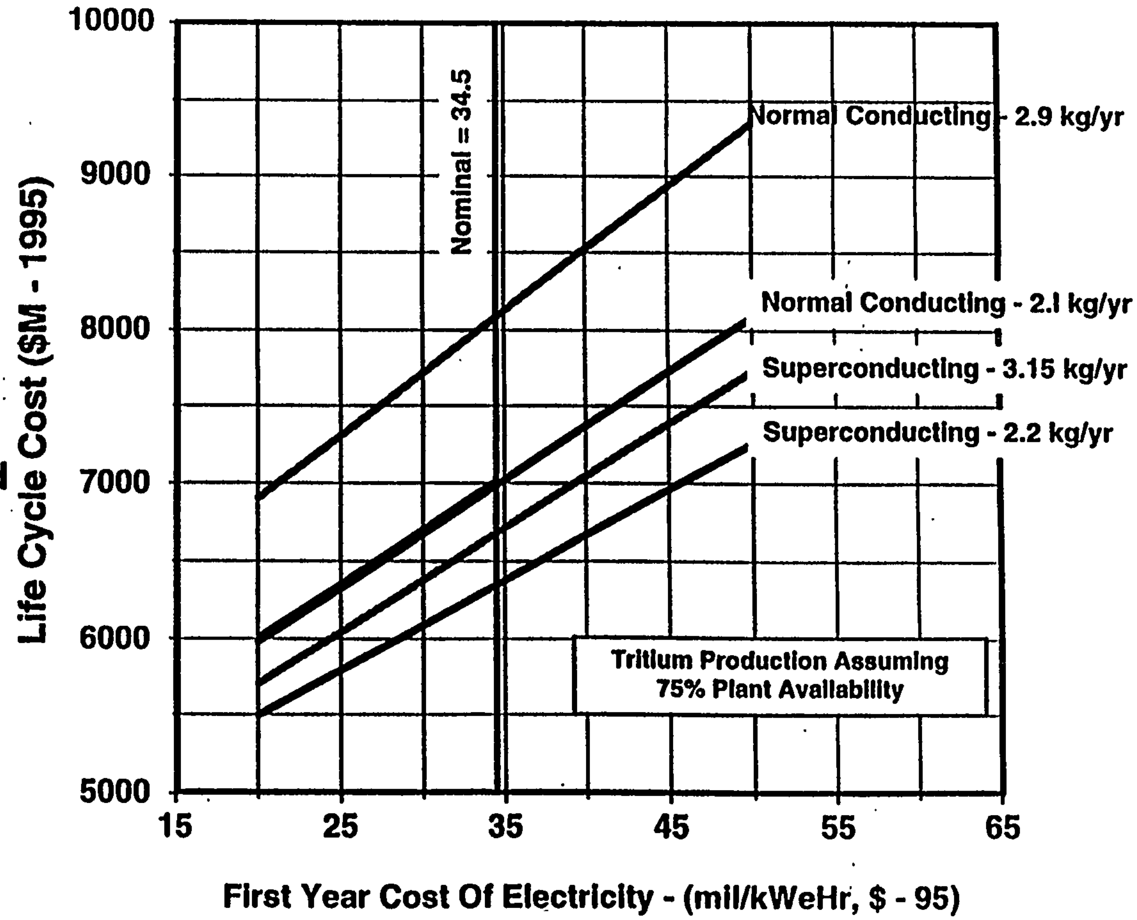
Life Cycle Cost Versus Cost Of Electricity

Trade Study Objective:
- Understand extent to which total life cycle cost is impacted by electricity cost

Major Considerations:
- Nominal elec. cost = 34.5 mil/kWeHr
- Variations between 20 and 50 mil/kWeHr
- Elec. cost denoted herein is first year cost in 1995 dollars.

Conclusions:

~ 35% sensitivity to uncertainties in indicated range



Comparison Of Reduced Time Operation At 1780 MeV With Full Time Operation at 1340 MeV To Produce Same Tritium Quantity

The baseline superconducting linac is capable of producing tritium at an instantaneous rate of 4.2 kg/yr (3.15 kg/yr at 75% availability) if it operates at a maximum coupler power of 210 kW to produce a 100 mA, 1780 MeV beam. If the coupler power level is reduced to 140 kW, then the beam energy is reduced to 1340 MeV and the production at 75% plant availability is reduced to about 2.2 kg/yr.

However, if the production requirement is to be lowered to this level, then it may be more economical not to reduce the coupler power and beam energy, but to operate the system at its full capability for a shorter period of time, corresponding to a full power system availability (really a plant capacity factor since the availability will be higher) of 52.4% (= 0.7 x 70%). This question derives from derives from the observation that the tritium production per unit energy at the higher energy (~3.15/1780) is 7.8% higher than the tritium production per unit energy at the lower energy (~2.2/1340). So if the electrical efficiency of the accelerator were the dominant cost component with the other costs fixed, it follows that part time operation at full energy will result in a lower life cycle cost than full time operation (i.e., 75%) at the reduced energy. The analysis shown on the following chart addresses this question.

A review of the scaling of various life cycle cost components is useful for presenting the advantages and disadvantages. The capital cost of the two systems is the same (they are the same accelerator). The annual electricity consumption for "part-time" operation of the sections of the linac through the medium β section, is reduced by 30% because part-time operation requires the same energy and current in these sections, but for 70 % as much time. In comparison, the annual electricity consumption of the high β section is 5% higher than for full time operation at the lower power level (the part time linac operates for 70% as long with 210/140 = 1.5 times as much rf power). However the electric consumption of the high β section is about the same because the klystrons operate more efficiently at full power. The part-time machine requires 30% fewer replacement and refurbishment parts (assuming that the failure rate is not a strong function of the operating power).

Our life cycle cost comparison included all of the above considerations, but ignored others such as the potential for reduced staff (potentially small life cycle cost impact) and the possibility of lower electricity rates for an APT plant that could be operated during off peak periods (a potentially large life cycle cost impact).

The overall result was a decrease in the estimated annual operating cost (relative to full time operation with 140 kW couplers to 1340 MeV) of 32 \$M/yr(-17%), resulting in a \$653 M (10%) savings in the life cycle cost when the tritium requirement is reduced to 2.2.kg/yr.

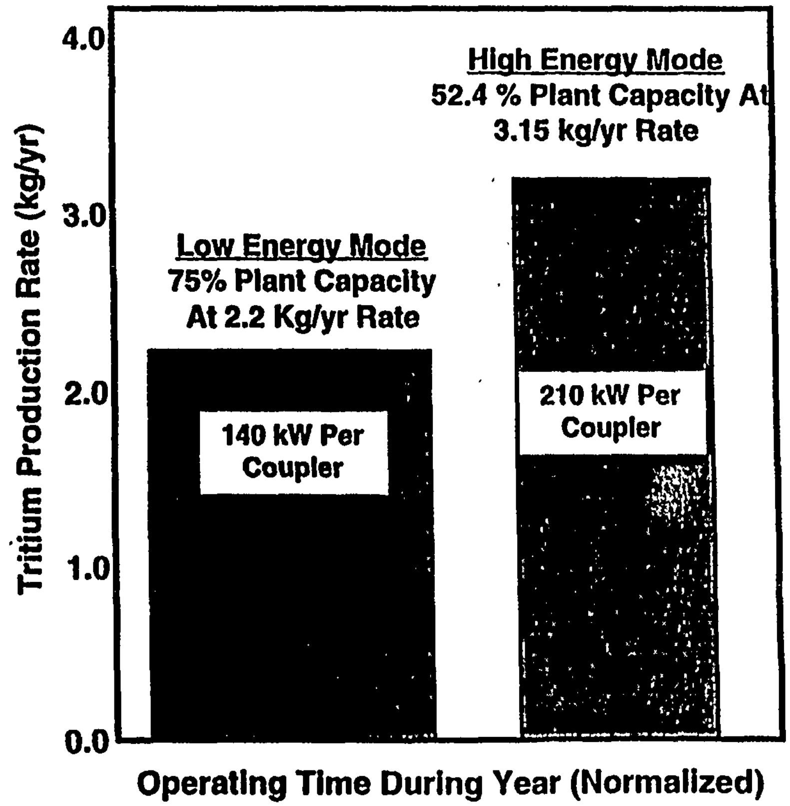
Comparison Of Reduced Time Operation At 1780 MeV With Full Time Operation at 1340 MeV To Produce Same Tritium Quantity

Trade Study Objective:

- Consider reduced time operation at 1780 MeV to produce same amount of tritium as full time at 1342 MeV

Major Considerations:

- *Baseline* 2 kg/yr production for 100 mA, 1342 MeV, 75% plant capacity operation includes ~10% margin. *Actual* production is ~2.2 kg/yr
- To produce 2.2 kg/yr with 3.15 kg/yr capability (100 mA, 1780 MeV, 75%) operate for 70% as long (52.4% capacity). Compared with *baseline*:
  - Low energy normal conducting linac and medium β SCL consume 30% less electricity
  - High β SCL consumes about same elec. (3/2 as much rf power, 70% as long, with higher Klystron efficiency)
  - Reduced requirements for replacement parts
  - Potential opportunities for smaller staff, lower elec. rates (not included in analysis)
  - More time for maintenance (lower risk)



Principal Conclusions:

- Operating cost compared with lower rate, full year operation decreases 32 $M/yr (17%)
- Life cycle cost decreases $653 M (10%)

Alternative Growth Strategies

Five alternative operating strategies and/or initial/final configurations to grow the SCL APT linac from a 2.2 kg/yr capability to a 3.15 kg/yr capability (both assuming nominal plant availability factor of 75%) were investigated in an effort to examine the "robustness" of the baseline design parameters. All five strategies, which are highlighted on the following chart, preserve the basic physics and engineering configurations of the baseline linac. They differ primarily in the rf coupler power and the provisions for rf transport to the superconducting cavities.

Strategy A is the baseline system, characterized by constant linac and tunnel length with an increase in the production from 2.2 kg/yr to 3.15 kg/yr to be accomplished by increasing the rf power output of each of the stations in the high β section from 560kW to 840 kW (into the cavities), which increases the coupler power from 140 kW to 210 kW and the beam energy from 1340 MeV to 1780 MeV.

Strategy B is the "part-time" scenario discussed previously. When the tritium requirement is 2.2 kg/yr the system is operated part time at its full capability.

Strategy C is an rf reconfiguration that initially provides only enough rf power stations (185) to operate the linac at the reduced level (140 kW couplers, 1340 MeV, 2.2 kg/yr). To accomplish this, the high β section is initially configured using the approach used for the medium β section (i.e., high power 2:1 splitters to create 6 balanced lines per station). When the machine is to be upgraded, the additional 52 rf stations are added (add one for every two existing stations in the high β section) and the 2:1 splitters are replace with existing and new 1:1 splitters. In this scenario, the above-mentioned splitters are located away form the linac in the rf hall, so that the transfer can be affected without disturbing the accelerator hall (except perhaps to install more capable rf couplers). This case and Case A both assume that the rf coupler will be tunable to match the rf system to the accelerating cavities over the 140 - 210 kW coupler power range.

Strategy D starts with the same, more efficient configuration as strategy C, but assumes that the coupler power will not be allowed to grow, but will be fixed at 140 kW. Therefore, to produce 3.15 kg/yr, the linac structure must be lengthened and the additional 52 rf stations must be provided along side. The longer tunnel that will ultimately be added and the increased HEBT cost to traverse it prior to the upgrade are included in the initial cost.

Strategy E assumes that the coupler power can be fixed at 210 kW from the outset. Therefore, the initial configuration is shorter (and uses the same amount of installed power as Strategies C and D). To produce 3.15 kg/yr, the linac structure must be lengthened and the additional 52 rf stations must be provided along side (at which time it becomes identical to the baseline). The longer tunnel and the increased HEBT cost to traverse it prior to the upgrade are, again, included in the initial cost.

Alternative Growth Strategies
(Depending Upon Achievable RF Coupler Power)

Initial 2.2 kg/yr — E (664 m); A, B, C, D (996 m)

Superconducting Sections: 664 m, 996 m, 1392 m

Growth 3.15 kg/yr — A, B, C, E (996 m); D (1392 m)

Strategy	Description	Growth 3.15 kg/yr			Initial 2.2 kg/yr		
		SCL Lgth.	RF Power/Coupler	No. RF Sta.	SCL Lgth	RF Power/Coupler	No. RF Sta.
A	Baseline	996	210	237	996	140	237
			Increase Coupler Power →				
B	Baseline With Reduced Operation Time** @ 3.15 kg/yr	996	210	237	996	210	237
			Operate Full Time →				
C	Lower Initial Installed RF Power	996	210	237	996	140	185
			Add RF Stations & Increase Coupler Power →				
D	Low Coupler Power Limit	1392	140	237	996	140	185
			Add Cryomodules & RF Stations →				
E	High Coupler Power Limit	996	210	237	664	210	185
			Add Cryomodules & RF Stations →				

* This is the number of rf stations in the 52.4% plant capacity factor compared with nominal 75%

Comparative Capital & Life Cycle Costs For Alternative Growth Strategies

The estimated capital and life-cycle costs for the five alternative operating strategies discussed on the previous pages are summarized and compared in the next chart. In each case, the initial capital costs include allowances for facilitating system growth (e.g., the initial cost for Case D includes a long enough tunnel to accommodate the longer accelerator that will be required for growth from 2.2 kg/yr to 3.15 kg/yr). However there is no assumption on how long the system might operate at the lower production level (i.e., the life cycle cost is based upon 40 years operation at the specified level).

As shown, the lowest life cycle cost, a 10% improvement, is provided by Case B (part-time operation at full capability). As noted earlier, the tritium production efficiency is about 8% higher at the higher energy. This advantage, combined with improved rf system efficiency at full power, drives the result.

Case C (lower installed rf power) results in a 2.9% lower capital cost and a 5% lower life cycle cost than the baseline (Case A) operated full time at the lower production level. The majority of the advantage results from more efficient operation.

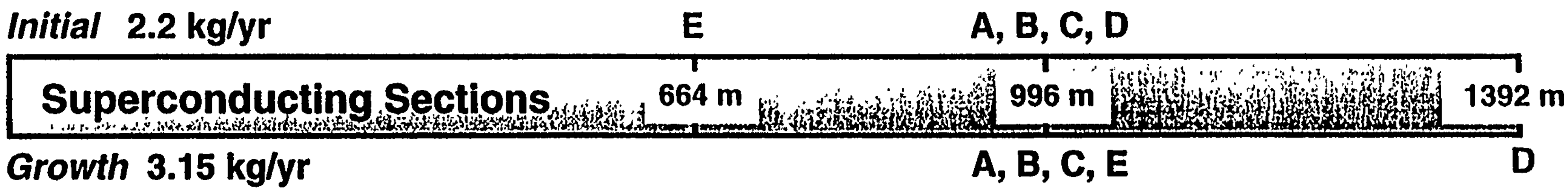
Case D (140 kW coupler limit) is more expensive than Case C because the initial configuration requires a longer tunnel, a HEBT to conduct the beam over the tunnel and, ultimately, a longer linac structure. It still provides some advantage at the lower production level. The cost penalty at the higher level is small, 4% of the capital cost and 1.6% of the life cycle cost.

Case E (210 kW couplers) provides the lowest capital cost at the lower production level, but the benefit is still less than 5% of the overall capital cost of the plant. The life cycle cost reduction is comparable to that of Cases C and D, about half of the savings that can be obtained from Case B.

With the exception of Case D (4% higher), the capital and life cycle costs after system growth to the 3.15 kg/yr level are nearly the same. This result is somewhat optimistic because the estimates do not the inevitable costs associated with a construction program disruption, which could be substantial.

In summary, there appears to be little incentive to move from the baseline. It provides the lowest life cycle cost at the lower production level without a substantial cost penalty. However, if the risk associated with the 210 kW coupler is high, the financial penalty for the 140 kW coupler power is small and quite manageable within the overall context of the APT life cycle cost.

Comparative Capital & Life Cycle Costs For Alternative Growth Strategies



Strategy	Description	Initial 2.2 kg/yr		Growth 3.15 kg/yr	
		Plant Capital Cost ($M)	Plant Life Cycle Cost ($M)	Plant Capital Cost ($M)	Plant Life Cycle Cost ($M)
A	Baseline	2526	6448	2526	6740
B	Baseline With Reduced Operation Time* @ 3.15 kg/yr	Same	-10%	Same	Same
C	Lower Initial Installed RF Power	-2.9%	-5.0%	+0.4%	+0.2%
D	Low Coupler Power Limit	-1.3%	-4.4%	+4.0%	+1.6%
E	High Coupler Power Limit	-4.5%	-5.6%	+0.2%	+0.1%

* 52.4% plant capacity factor compared with nominal 75%

2.3 APT Reliability/Availability/Maintainability (RAM) Summary

Before summarizing the results of the Reliability / Availability / Maintainability (RAM) activities for the APT linac conceptual design effort, it is important to set the stage by reviewing the objectives for this activity. These objectives are to:

- **Establish reliability and maintainability requirements at the subsystem and component levels**
- **Identify system sensitivities to RAM uncertainties**
- **Influence the level of design redundancy**
- **Improve estimates of the life cycle cost (spares and replacements)**
- **Identify areas for potential R&D**

Typical results in each of the above areas are summarized in this section. The reader is referred to Sections 3.4 and 4 for further discussion.

Derived System-Level RAM Allocations

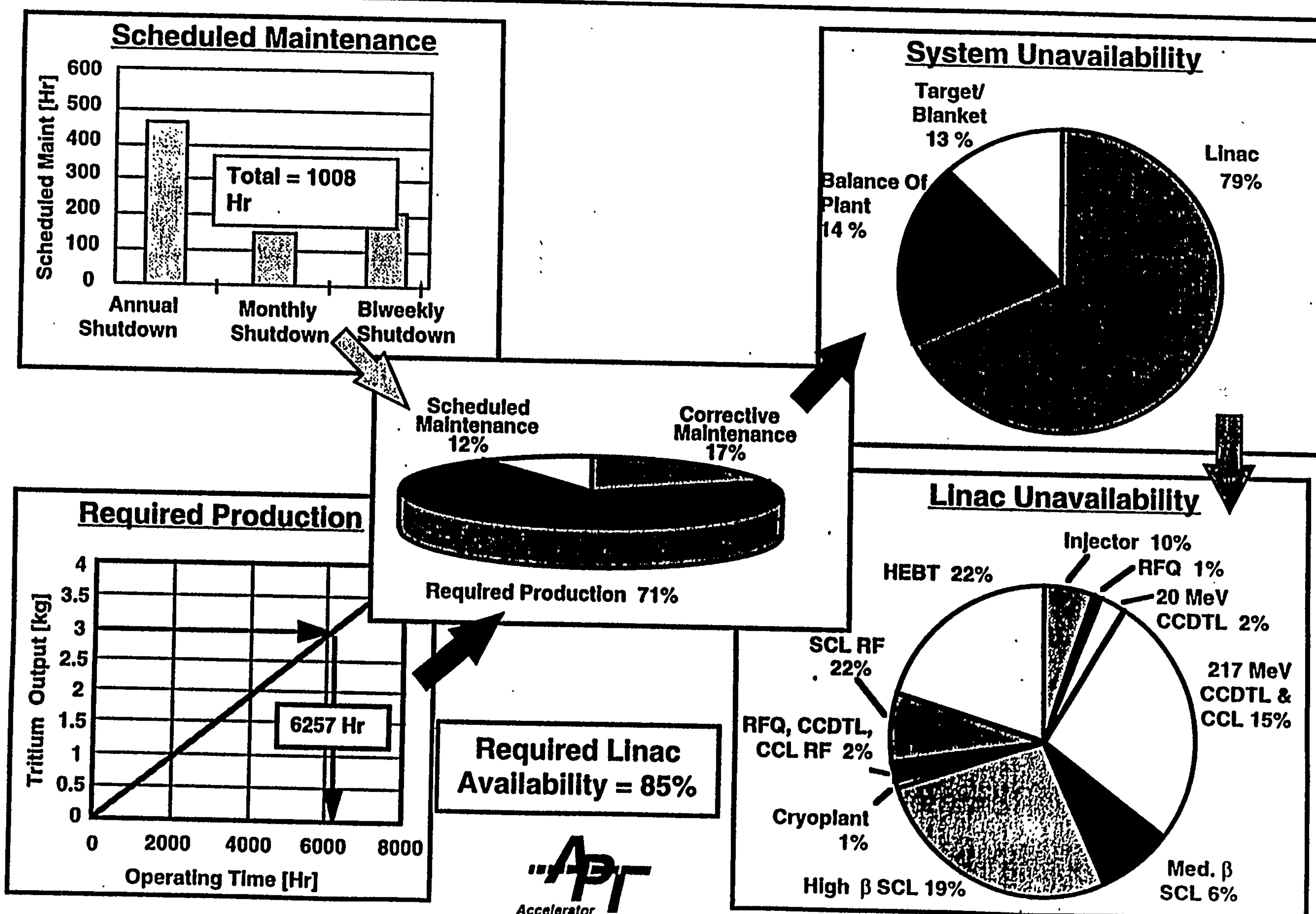
The derived system-level RAM allocations, which represent a reasonable balance between the flow-down of operational requirements (i.e., required annual tritium breeding) and the flow-up of subsystem and component capabilities, are shown on the next page.

As indicated, with an instantaneous tritium production rate of 4.2 kg/yr, the APT plant must operate for 6257 hours per year to produce the goal quantity of tritium (3.0 kg/yr). This represents operational system availability of 81% (equivalent to the plant capacity factor assuming the linac operates only at full capacity). After allocation of 1008 Hr for scheduled maintenance, which represents 12% of the calendar year, 17% of the calendar year is available for corrective maintenance. Accordingly, the system inherent availability requirement is 81%, and its unavailability is 19%. Of this, 79% is allocated to the linac and its supporting systems. The resulting linac availability must be 85% during scheduled operation [0.85 = 1-0.19*0.79].

The allowance for linac unavailability is distributed among the major subsystems as indicated in the pie chart at the lower right of the next page. As shown, the linac unavailability is dominated by the unavailability of the low, medium and high energy linac accelerating structures (much of which is driven by the allocated unavailability of the rf couplers, which will be highlighted in the next several charts).

The unavailability of the rf power stations is less than originally anticipated. The reason is that most failures in individual stations can be repaired on-line while the balance of the system remains operable. Nevertheless, it is helpful to keep in mind that, for example, with an assumed klystron Mean Time Between Failures (MTBF) of 25,000 hours and 237 rf stations in the APT linac system, a klystron will be repaired, on average, every ~100 hours.

Derived System-Level RAM Allocations



Required Linac Availability = 85%

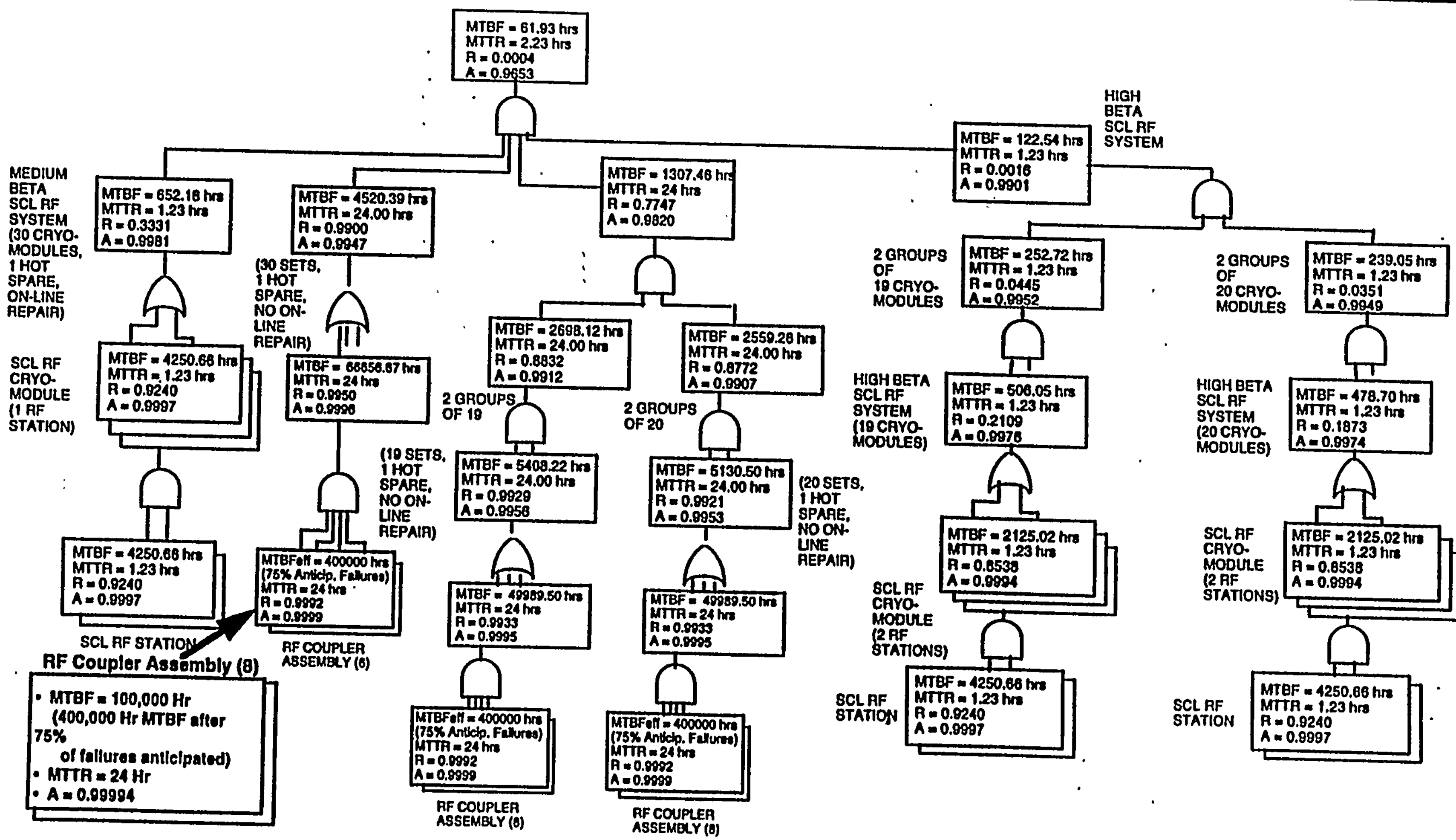
APT Accelerator Production of Tritium

Example RAM Model/Logic: SCL RF System

A typical data/logic structure incorporated into the APT RAM model is indicated in the next chart. As shown, the model encompasses a hierarchy of operational criteria for equipment of increasing complexity based upon combination of "and" & "or" logic. In the example shown, the "and" logic applies to the various equipment that comprises each of the SCL RF blocks corresponding to individual cryomodules. That is, to be operable, a given "rf cryomodule" requires the operability of each of its constituent assemblies. The "or" logic, which, for example, applies to the operability of individual rf cryomodules in groups of 19 or 20 in the high β section, is used to account for spares and operable failures (e.g., m spares or operable failures out of n units). Because the "or" logic can apply to any of several operational situations (e.g., ability to repair some equipment on-line without need for system shutdown), one of several mathematical models is used to model this situation. In the case of the high β rf cryomodules, one of each group of cryomodules is allowed to fail without loss of system operability. However, when it does fail, the rf stations and other cryomodules in the linac must be reprogrammed to compensate for the loss of energy gain in the failed cryomodule. Therefore, we include the time to retune and restart the linac in the analysis. On the other hand, if the cryomodule failure results from a failure of the cryomodule itself, then it can not be repaired on-line (see Section 3.4 for illustration of the RAMI model for the SCL linac). In this case, there would be a significant loss of availability if more than one cryomodule in a chain of 19 or 20 fails. The maximum allowed failure condition in the high β linac, four failed cryomodules, one in each chain, is expected to be rare.

Also indicated in the chart, each piece of equipment in the RAM model is characterized by at least two input data items: the mean time between failures (MTBF) and the mean time to restored production (MTTR). In some cases additional data items are used. For example, as indicated in the expanded box for the rf coupler assembly, where a fraction of the failures can be anticipated and corrected during scheduled operation, the MTBF is effectively increased by the factor 1/(1-Fraction Anticipated). Other inputs to the model describe the number of identical components in a chain, the number of spares, the repair policy (e.g., on-line or off-line) and the time to restore system operability depending upon how many components have failed. At each level we calculate the equipment availability (probability that it will be able to operate during scheduled operations) and reliability (probability that it will remain operable for a fixed period of time [2 weeks in above example]).

Example RAM Model/Logic: SCL RF System



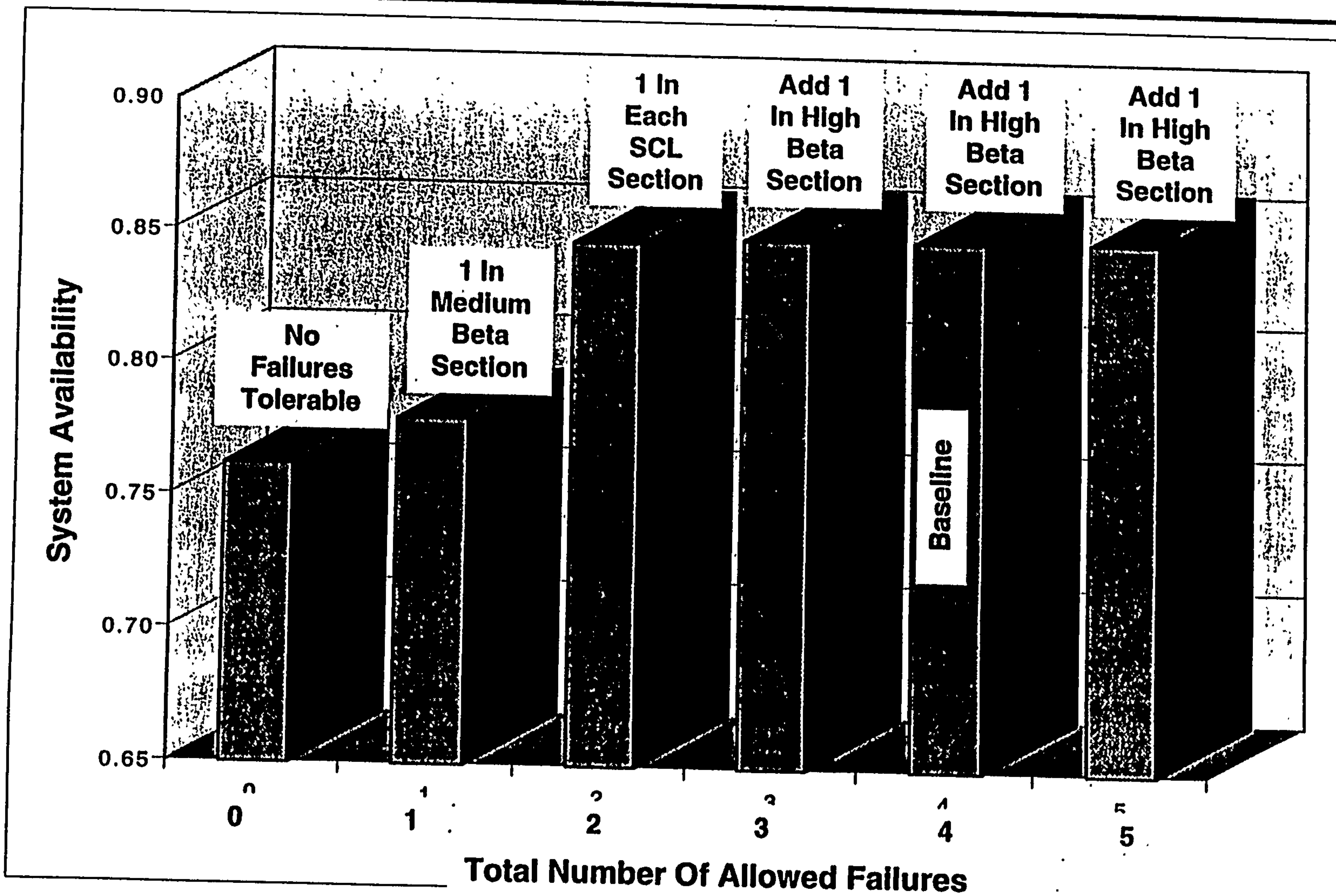
Allowed Number Of Cryomodule Failures

The normal conducting APT linac (as well as the normal conducting low energy section of the superconducting linac) uses supermodules to provide redundancy of the rf system. However, the superconducting linac has no supermodules in the high energy section. It relies, instead, on the ability of the system to continue operation and tritium production despite the inoperability of a very small number of 16.8 MeV cryomodules (due to either failure of the cryomodule itself or failure of one of the two rf stations that power it). The ability of the SCL to operate through the failure of one or more cryomodules (a question that must ultimately be resolved by detailed simulation of the SCL beam dynamics) depends upon the the energies and separation of the failed cryomodules. The number of allowed failures is likely to exceed one, but is not likely to exceed five.

It is, therefore, of interest to determine how many allowed cryomodule failures are likely to be required under typical conditions. In performing this analysis we considered several cases, as shown on the following page. First, it was assumed that there would be no allowed failures in either the medium or high β section of the SCL. In this case, the achievable linac availability is only 76.2 % (reduced from 85.0 % baseline), so the tritium production is reduced from 3.00 kg/yr to 2.69 kg/yr. If we increase the number of allowed cryomodule failures to 2 (one in each section of the SCL), then the availability improves to 84.9%, resulting in an annual tritium production level of 2.99 kg/yr.

Although the baseline RAM model shown earlier allows for up to 3 additional failures in the high β SCL, these results indicate that this capability is not likely to be required. Put another way, the failure of 2 cryomodules in a string of 19 or 20 (baseline model) is expected to be rare.

Allowed Number Of Cryomodule Failures



RAM Sensitivities to Data Uncertainties

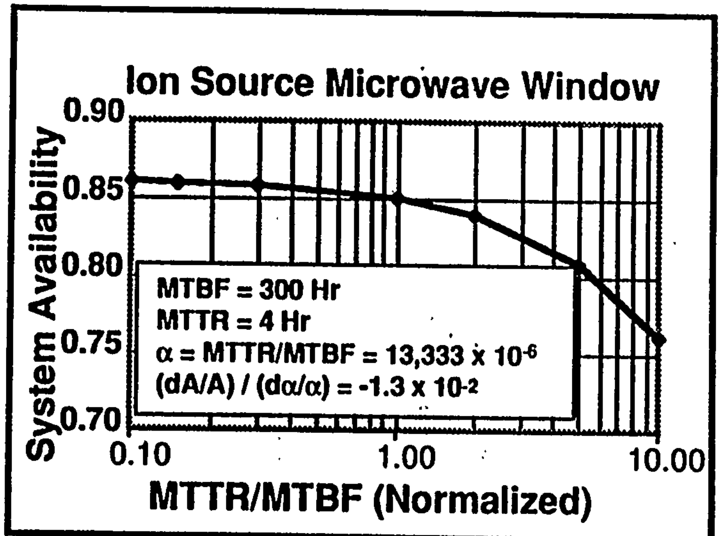
The following chart describes the sensitivity of the linac system availability to certain key drivers. For this analysis we recall a previously defined figure-of-merit (α = MTTR/MTBF) and define a new figure-of-merit, $(dA/A)/(d\alpha/\alpha)$, which represents the sensitivity coefficient that expresses the fractional change in system availability per unit of fractional change in α. The component with the highest sensitivity coefficient is the component for which the system availability is most sensitive to uncertainties in the value of α.

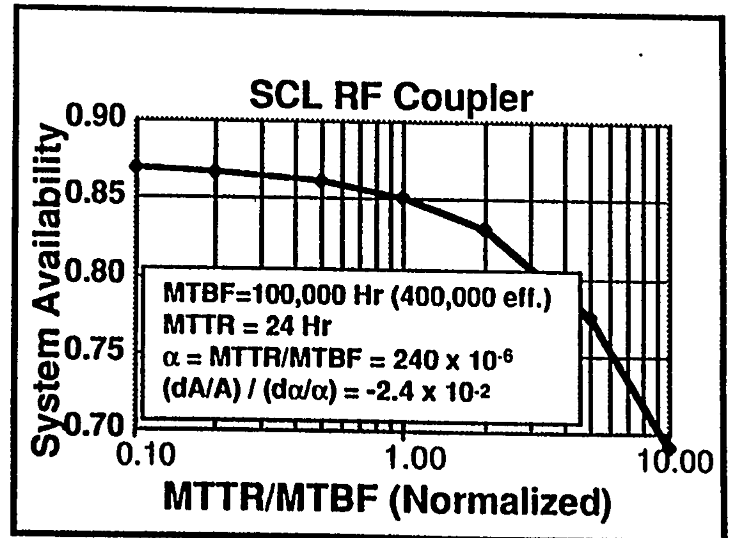
As shown, the linac availability is most sensitive to the RAM performance of the rf coupler (sensitivity coefficient of $-2.4\ 10^{-2}$) and is relatively insensitive to the RAM performance of the klystron (sensitivity coefficient of $-7.7\ 10^{-4}$) .

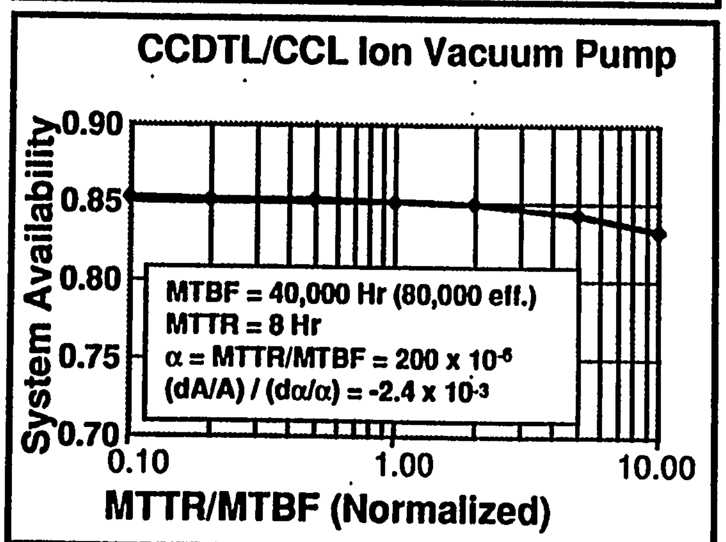
It is important to note that the system does, in fact, achieve acceptable performance under the assumed rf coupler RAM capabilities. [Recall, for example, that the failure of 2 cryomodules in a string of 19 or 20 is rare]. However, these results show that if the coupler performance were to be further degraded, than the probability of suffering multiple coupler failures within a string would be less unusual, and could result in a significant performance degradation.

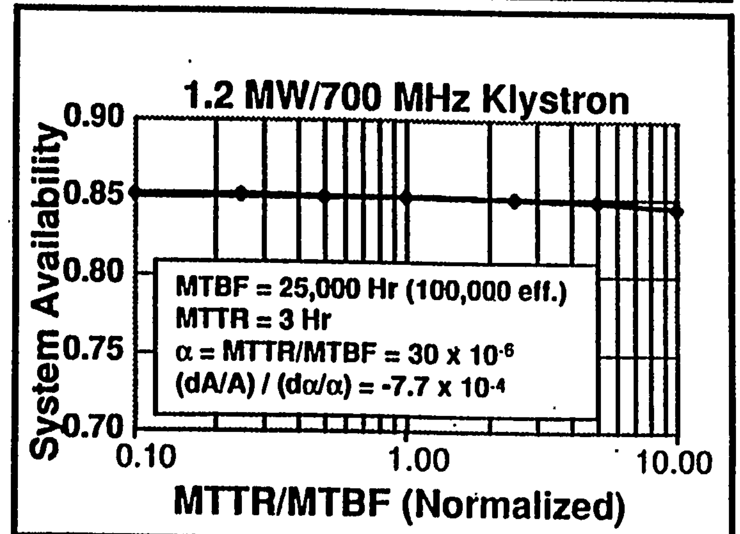
The lower sensitivity coefficient of the klystron results from its decoupling from the RAM calculation. That is, when a klystron fails, it can be repaired on-line while the system continues to operate. Since the MTTR is much less than the MTBF, it is rare that a second klystron fails while the first is under repair and more rare that this second klystron is in the same string of cryomodules as the first.

RAM Sensitivities to Data Uncertainties









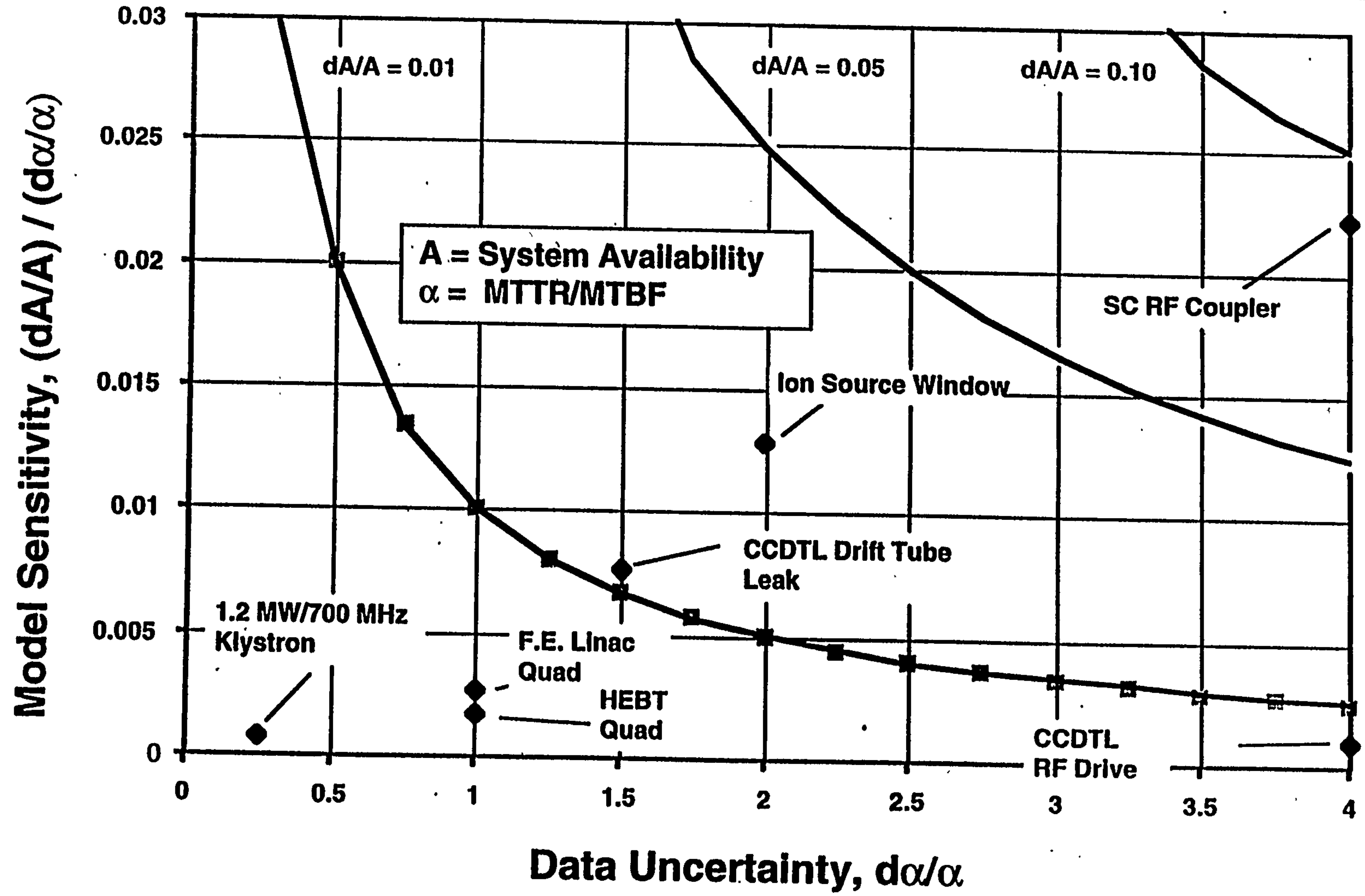
APT Linac RAM Importance Analysis

The following chart combines the sensitivity coefficient, $(dA/A)/(d\alpha/\alpha)$ (y-axis), with the uncertainty in the RAM performance, $d\alpha/\alpha$. The lines across the chart represent points having equal fractional loss of availability, dA/A. [This chart is directly analogous to the probability versus consequence charts that are used in the nuclear industry to illustrate the risk due to a particular set of potential accident scenarios.]

As shown, the component with the highest potential impact on the linac availability is the rf coupler. First, it has the highest sensitivity (shown earlier). Second, its RAM performance, especially the failure rate (1/MTBF) of the vacuum window (1/100,000 hours) and the ability to diagnose a large fraction of window failures *a priori* (3 of 4 assumed in the model) are both highly uncertain. Fortunately, even for this most sensitive component, the potential impact is manageable. If its performance were to be 4 times worse, the overall impact on APT system availability will be about 8% - significant, but manageable. Indeed, referring to an earlier calculation (Marginal Cost Per Unit Of Tritium Production), if desirable, this potential loss could be compensated (really insured against) by building additional capacity into the linac. The linac cost for an additional 8% capability is estimated to be $43 M, or 3.7% of the total linac cost.

As expected, the klystron can be found in the lower left hand corner of the chart. The sensitivity of the RAM to its performance is low. There exists a reasonable data base (e.g., CERN 352 MHz, 1300 kW Superklystrons) from which to derive its likely RAM performance.

APT Linac RAM Importance Analysis



Accelerator Production of Tritium

NORTHROP GRUMMAN

RF Window Failure Modes

The rf coupler, which includes the vacuum and guard windows shown on the next page, is a key RAMI driver. This results from the large number of couplers - 644 in the high β SCL, and about 800 including the low β SCL cryomodules. The current RAMI analysis has led to certain improvements in the rf drive which will be included in the next version of the RAMI model and analysis effort. The gist of the new idea is to add a "guard" window which will protect the system by limiting the amount of gas which can make its way into the cavity so that a potential failure of the vacuum window does not create extensive contamination problem and only one cryomodule has to be replaced to restore the system to production. With a conditioned and refrigerated cryomodule spare in standby, the MTTR for this replacement is estimated at about 24 hours. CEBAF has performed such cryomodule replacement operations in about half that time.

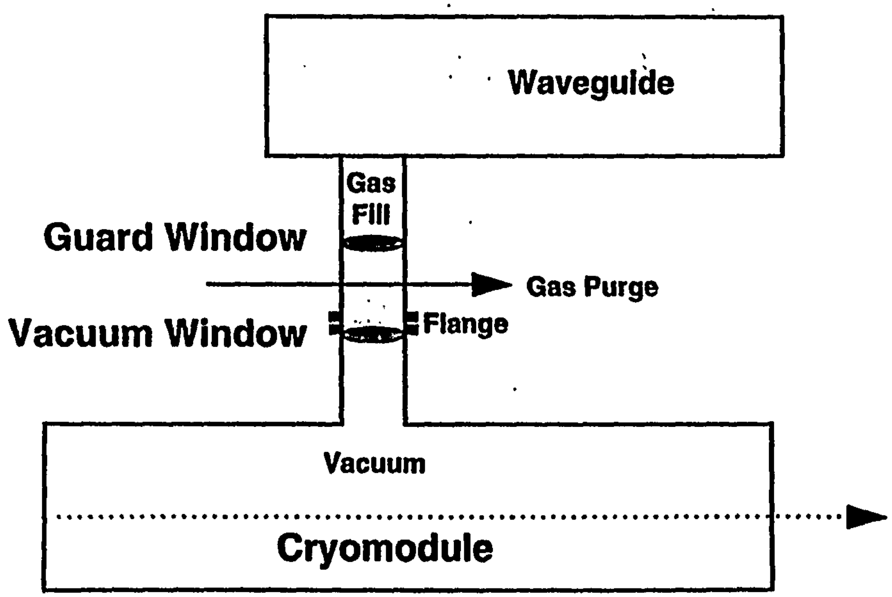
The addition of the guard window does not affect availability of the rf coupler system, contrary to what might be expected, because failures of the guard window will have minimal impact on system availability (provided they are limited in number and frequency). The MTBF of the guard window is expected to be high because it is cooled on both sides by the air flow. The MTTR for the guard window consists only of the time required to turn off the rf station and to rephase the rf field as necessary to compensate. Of course, the production rate will be somewhat reduced, but the window will be replaced at the next maintenance opportunity.

To incorporate this new idea in the RAMI modeling, changes will be made in the next phase of the analysis to include the guard window, the effects of the diagnostics on anticipated failures for both windows, the varying MTTR values depending on the failure mode, and the reduced production capacity in the degraded mode.

RF Window Failure Modes

Rationale For Guard Window:

- Limits volume of gas intrusion into the SCL in case of catastrophic failure
- Minimal impact on availability with continuing operations till the next maintenance period



Guard Window Failure:

- Excessive sparking or crack: rephase RF system & continue
- Long MTBF (both sides cooled)
- Short MTTR (rephase only)
- Very small effect on availability

Vacuum Window Failure:

- Excessive sparking: rephase RF & continue till next maintenance
- Crack: small gas release to cryomodule (replace only one cryomodule)
- Shorter MTBF
- Longer MTTR
- Crack possible only if detection fails

Implications For RAM Model Enhancement:

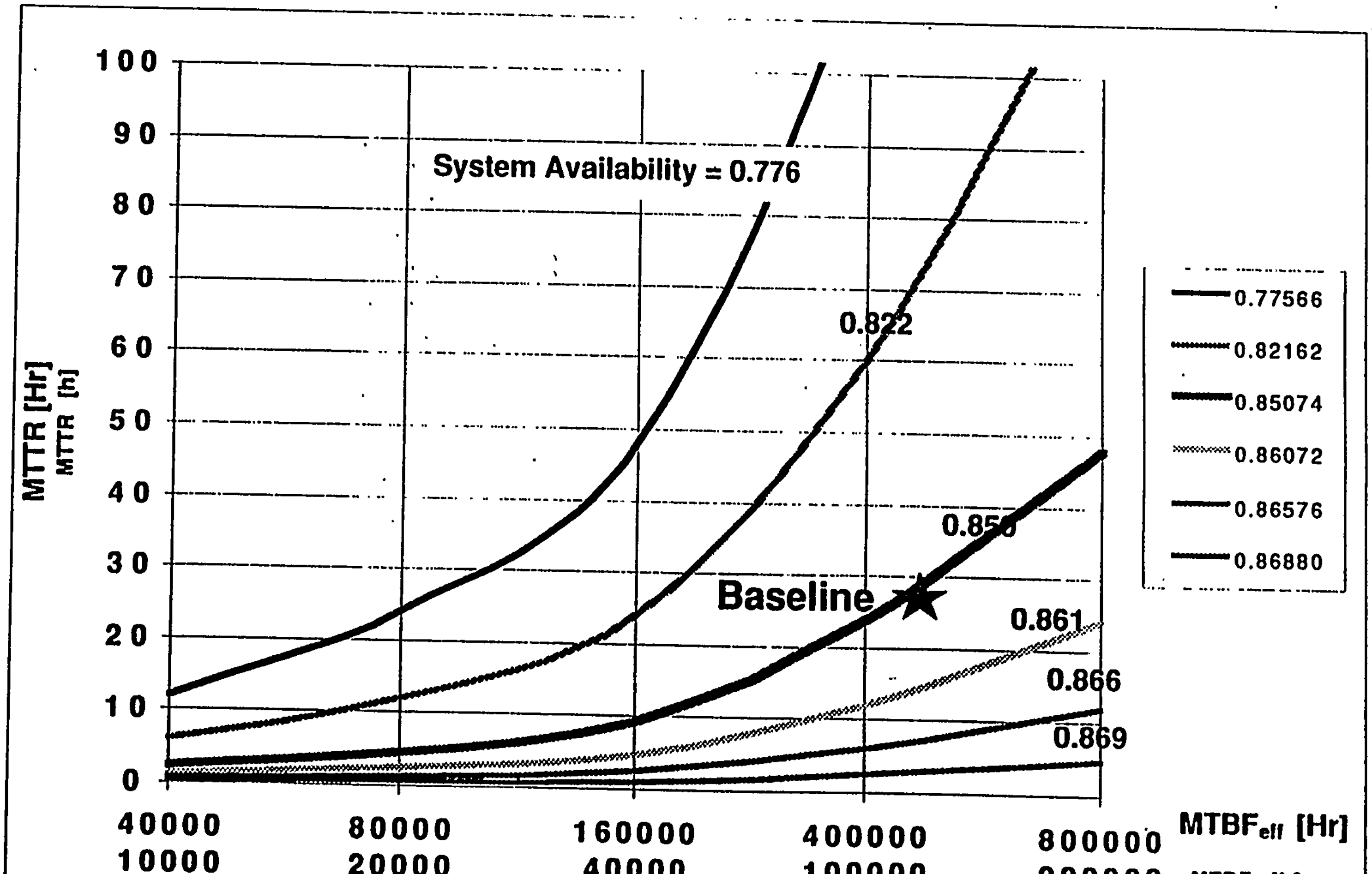
- Include guard window for completeness
- Include diagnostics for anticipated failures effects for both windows
- Include tfe effect of reduced production capacity in degraded mode

MTTR vs MTBF For SCL RF Coupler

One consequence of the RAM modeling algorithms used in our analysis is that the individual values of the MTBF and MTTR are, in all cases, combined to form a dimensionless figure-of-merit, α = MTTR/MTBF, which drives the calculation of the linac availability. Therefore, for a given value of α (representing a given level of system availability), the required MTBF can be determined by the achievable MTTR, and vice versa.

The following chart indicates this relationship for the rf coupler example discussed earlier. For example, if the achievable MTBF is not 100,000 Hr, but 40,000 Hr, then the allowed MTTR to maintain the baseline availability is reduced from 24 Hr to no longer than about 10 Hr. Conversely, if the MTTR is to remain at 24 Hr, then the linac system availability goal must be reduced by about 3%.

MTTR vs MTBF For SCL RF Coupler



Note: $MTFF_{eff}$ = MTBF/(1-Fraction Anticipated Before Failure)

RAM Comparison for Normal Conducting and Superconducting Linacs

- The RAM performance of the superconducting linac (1780 MeV, 100 mA) was discussed in the earlier charts. It has an instantaneous tritium breeding rate of 4.2 kg/yr which, combined with a linac availability of 85% and a plant availability of 80.6% leads to an annual tritium production of 3.0 kg/yr.

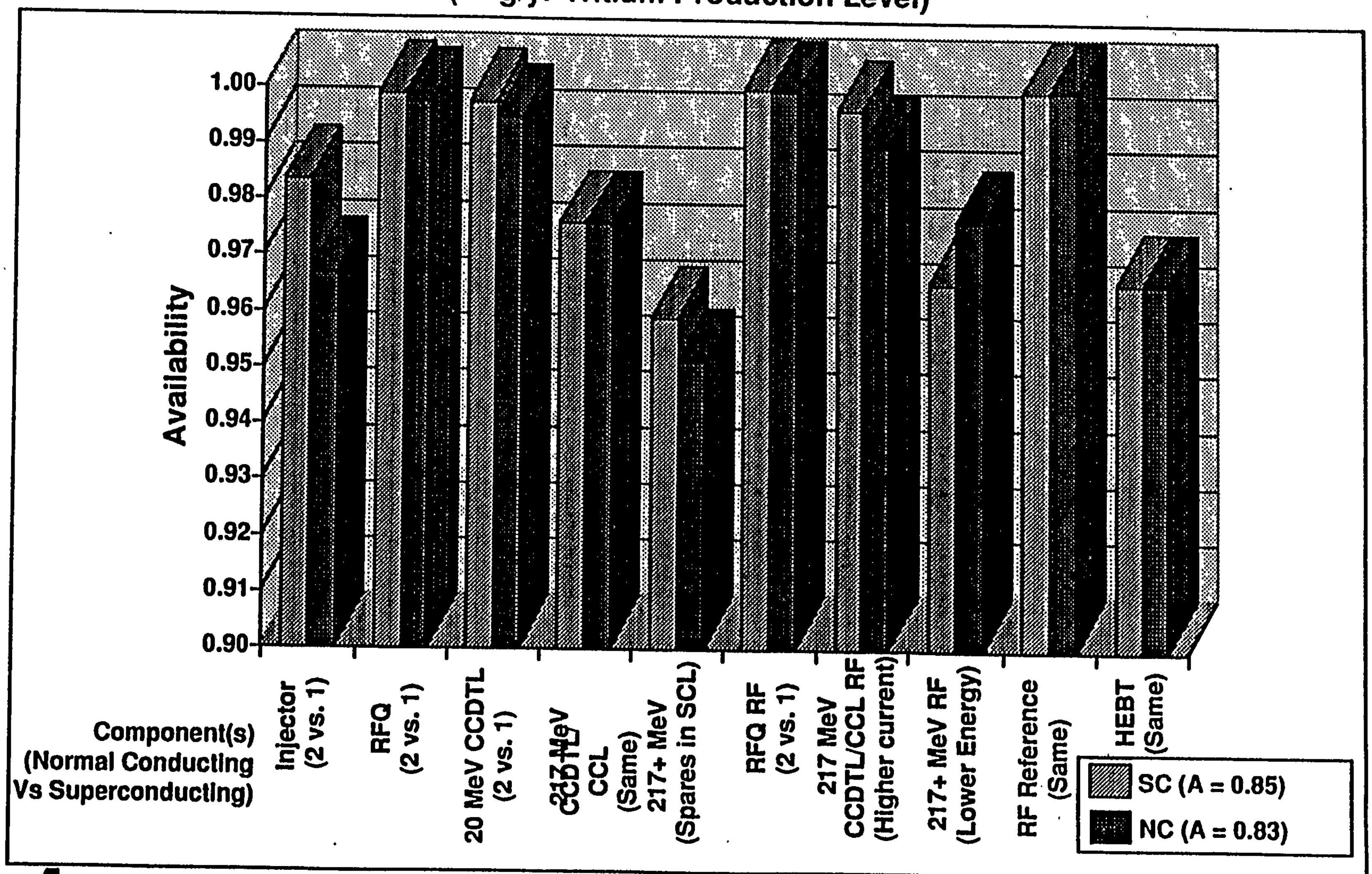
- The normal conducting linac (NCL) is the 136 mA, 1300 MeV baseline with a current funnel at 20 MeV. The NCL makes extensive use of rf supermodules, each of which is comprised of several (typically 8) rf stations, including one spare to improve system availability. Our RAM results, indicate that despite this availability enhancement (see also Sections 3.4 and 4.2), the NCL can achieve only 77% plant availability (corresponding to 83 % linac availability), resulting in an annual tritium production of 2.7 kg/yr.

- Importantly, additional RAM studies indicate that a more efficient two production level NCL operating scenario can be implemented without any design changes or added capital cost if the beam current can be increased to the maximum level consistent with the installed power in the supermodules. By operating all of the eight rf stations in each supermodule at full power (no spare), it will be possible to increase the beam current by about 20% (164 mA in the CCL, 82 mA in each low energy leg). In this first level of operation the linac availability is lower than previously discussed, but the production rate is 20% higher, resulting level of annual NCL tritium production that is roughly the same as reported above. However, when an rf station fails the system need not be shut down. Instead, it can be operated at a reduced level of beam current consistent with the remaining rf power (the original 136 mA) while the failed rf station is repaired, adding to the net tritium production. Results indicate that for this operating scenario, the the net production relative to the original mode will be increased by almost 20%, resulting in an estimated production for this machine of about 3.2 kg/yr, which exceeds that of the SCL.

- The reader is reminded that detailed RAM analysis based upon the specific SCL and NCL configurations are provided in Section 3.4.

RAM Comparison for Normal Conducting and Superconducting Linacs

(3 kg/yr Tritium Production Level)



2.4 Summary Of Manufacturing Schedule Evaluation

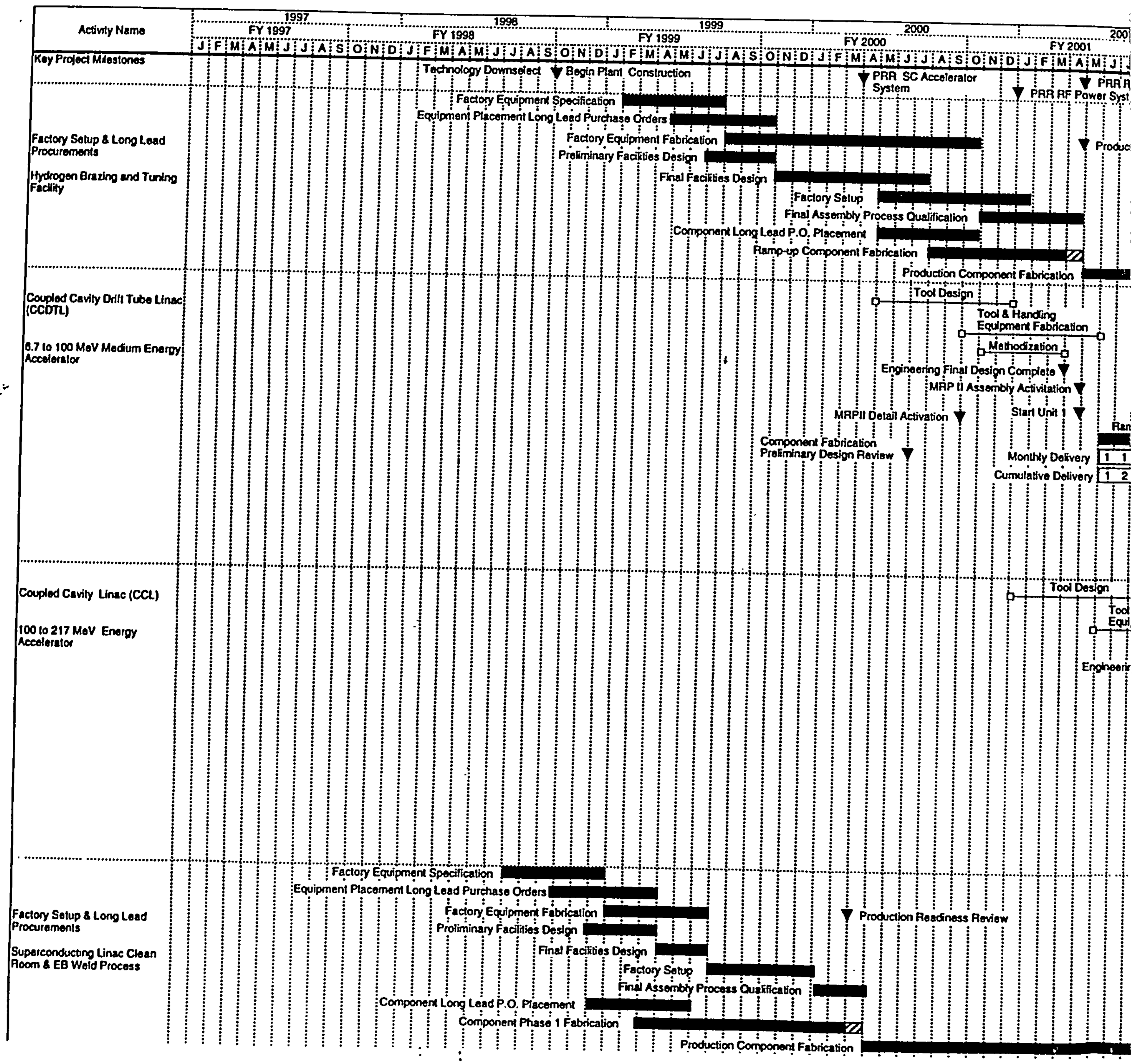
Northrop Grumman's Manufacturing Schedule Evaluation task involved reviewing existing APT plans (provided by Los Alamos) to provide an independent assessment of the required manufacturing process flow and schedule for both the normal conducting and superconducting APT linacs. These flows and schedules included all aspects of procurement, manufacturing, fabrication, testing and integration of the APT accelerator structures and rf power systems. Possibilities for improvement in areas involving manufacturing producability, cost, and scheduling were identified.

The following assumptions were used throughout:

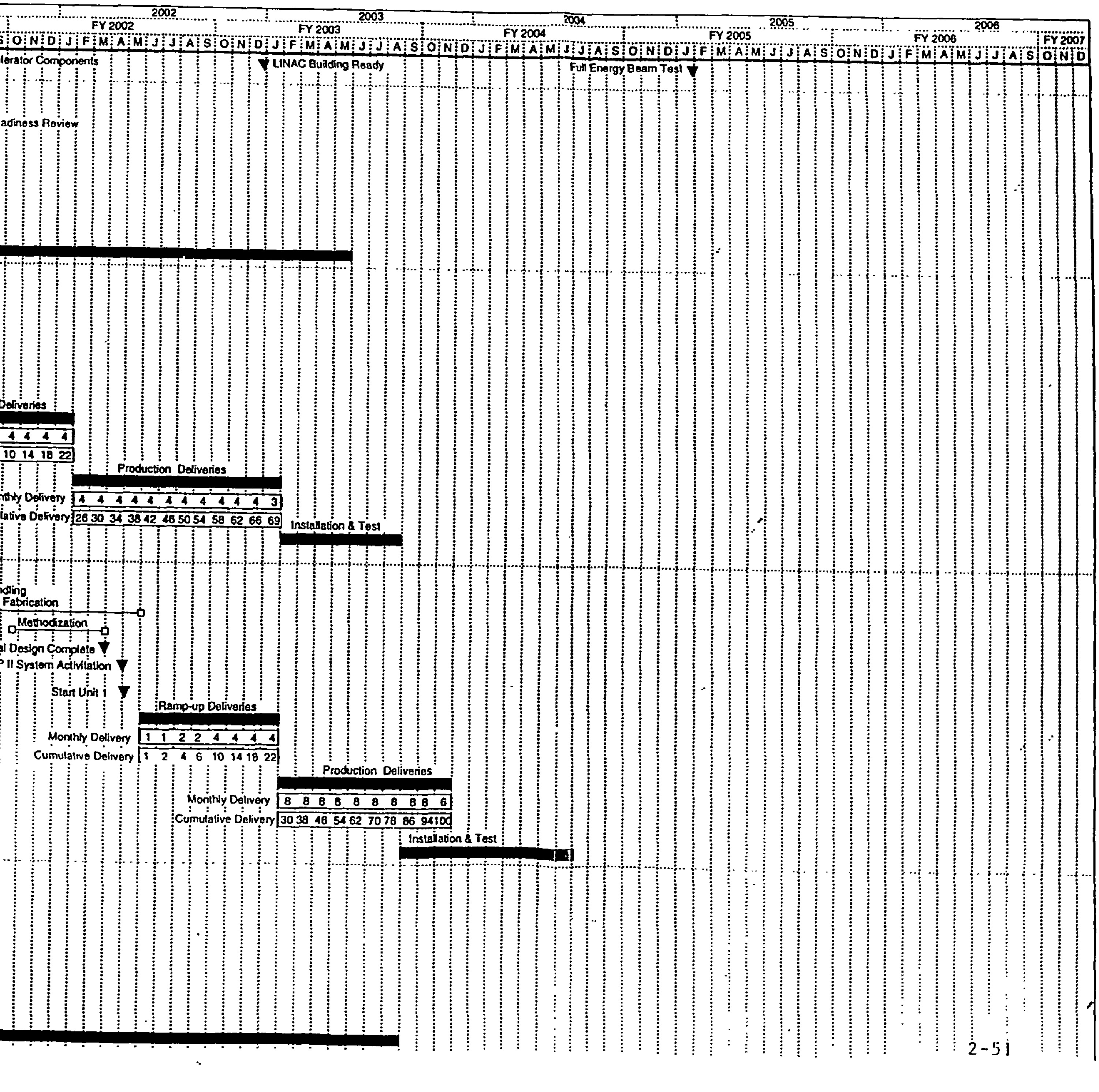
- The Los Alamos-developed *"Integrated SCRF Accelerator Schedule, 4/3/96 (Incremented FY97 Funding"* provided a starting point for the evaluation. This schedule specified the following major milestones:
  - Technology downselect 10/1/98
  - Linac building complete 1/1/03
  - Full energy beam test 4/1/06
- Phased Preliminary Design Reviews (PDR's) will be conducted prior to placing long lead purchase orders
- Production Readiness reviews (PRR's) will be conducted at the fabrication facilities to ensure assembly qualification prior to fabrication of the first components
- Tool design and tool material handling fabrication will be completed prior to final process qualification
- A ramp-up phase will precede the production phase, where peak delivery rates are to be attained
- Final assembly, installation and test of RF Power System on-site at SRL after RAMI demonstration phase
- Installation and testing of linac and rf power modules started prior to completion of tunnel and klystron gallery (phased occupancy)
- Final installation and test activities will be successful. No a *priori* allowance for program interruptions.

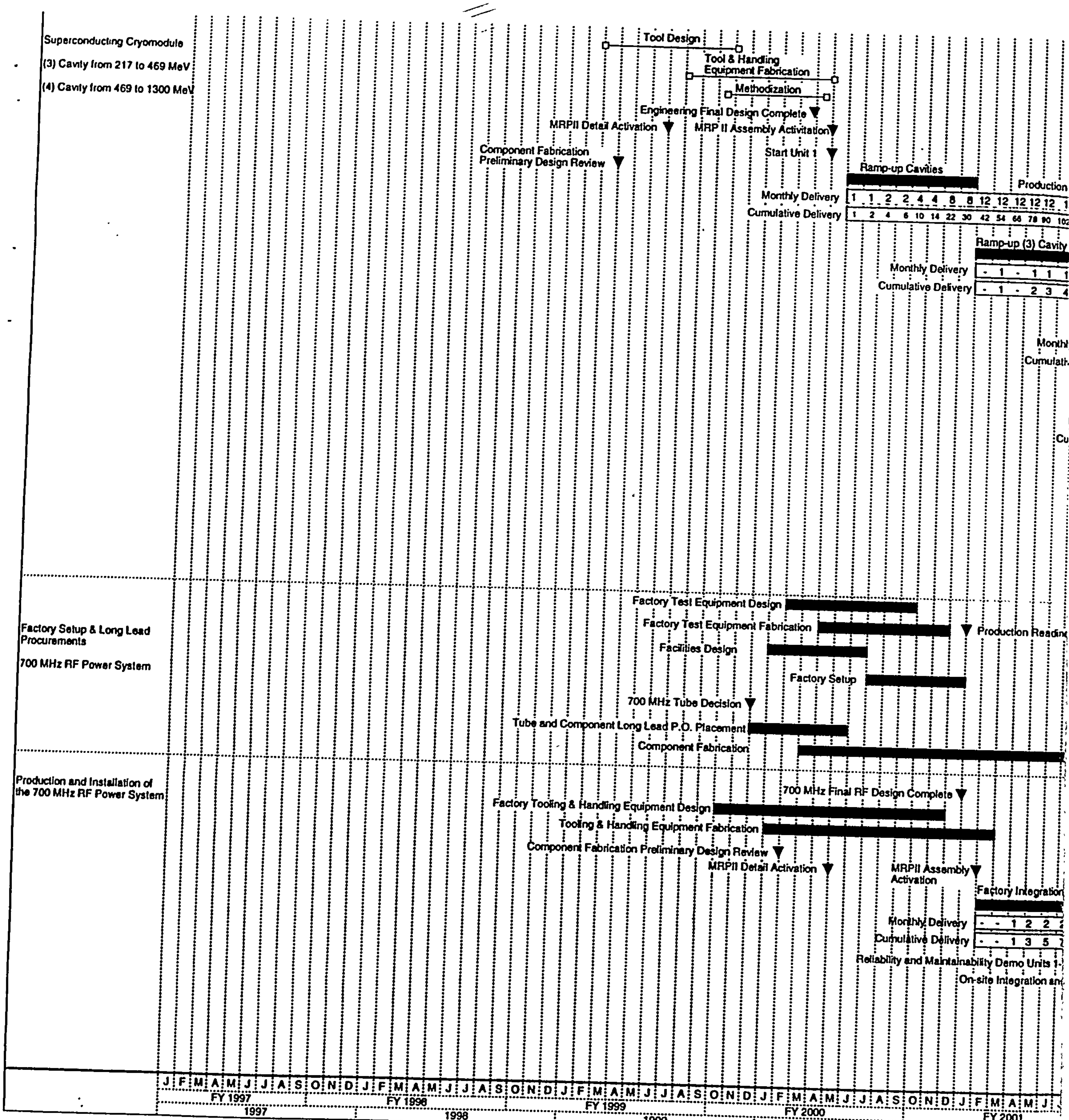
The results of this effort, summarizing our evaluation of the schedule for the superconducting linac (SCL), are provided in Section 5 and summarized on the following two pages (both fold-outs). They indicate that it might be possible to complete the SCL cryomodules and their rf power stations early enough to realize the full energy beam test about one year earlier than the March 2006 date projected in the April 1996 schedule.

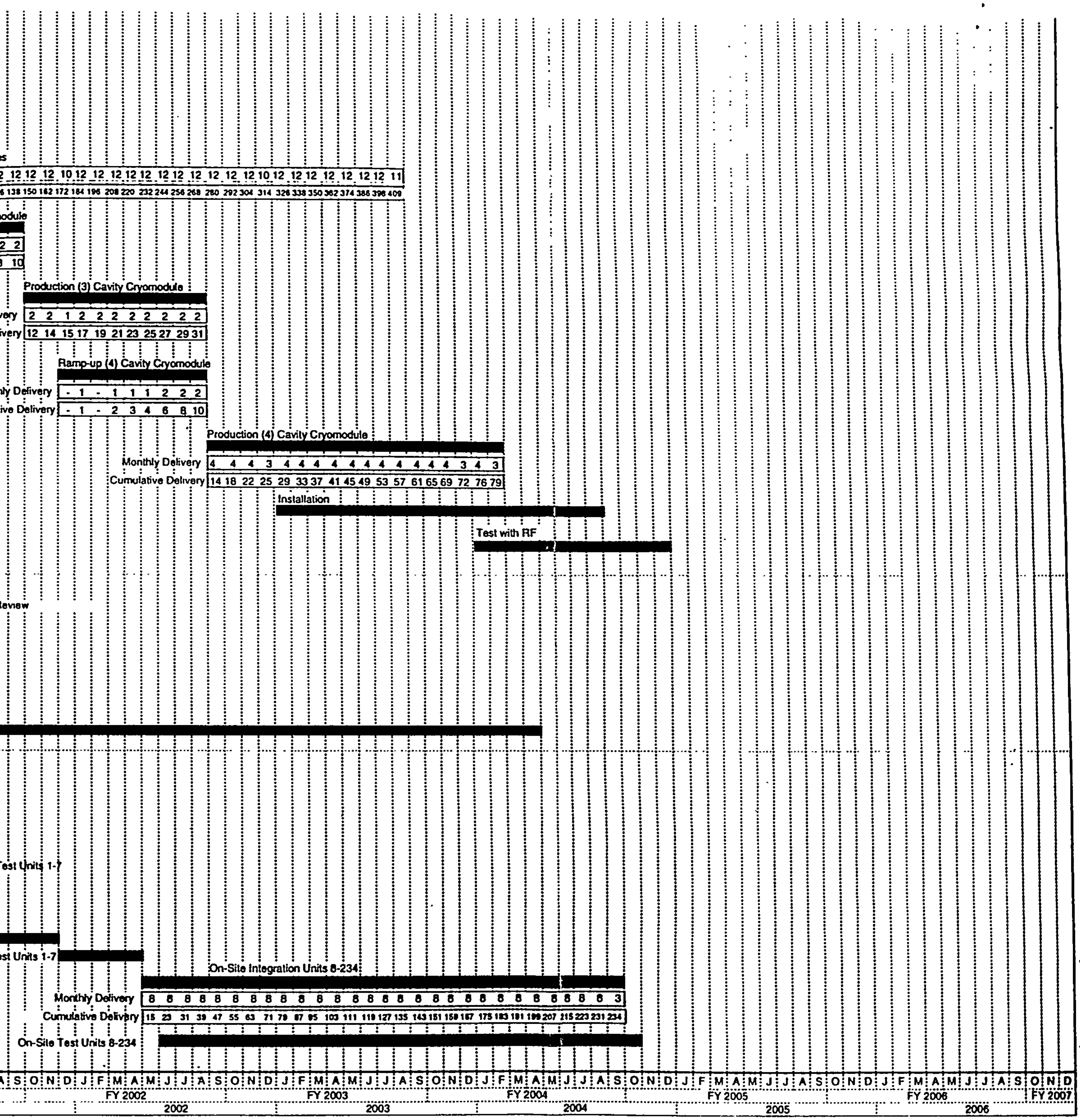
Preliminary Sche
APT Superconducting Manufacturi
Rate Production 6.7 thru 1300 MEV C



le Assessment
Flow for Alternate Configuration
TL - CCL - SCL - RF Power Supplies




Superconducting Cryomodule
(3) Cavity from 217 to 469 MeV
(4) Cavity from 469 to 1300 MeV
Tool Design
Tool & Handling Equipment Fabrication
Methodization
Engineering Final Design Complete
MRPII Detail Activation
MRP II Assembly Activation
Component Fabrication Preliminary Design Review
Start Unit 1
Ramp-up Cavities
Production
Monthly Delivery
1 1 2 2 4 4 8 8 12 12 12 12 12
Cumulative Delivery
1 2 4 6 10 14 22 30 42 54 66 78 90
Ramp-up (3) Cavity
Monthly Delivery
- 1 - 1 1
Cumulative Delivery
- 1 - 2 3 4
Factory Setup & Long Lead Procurements
700 MHz RF Power System
Factory Test Equipment Design
Factory Test Equipment Fabrication
Production Readin
Facilities Design
Factory Setup
700 MHz Tube Decision
Tube and Component Long Lead P.O. Placement
Component Fabrication
Production and Installation of the 700 MHz RF Power System
700 MHz Final RF Design Complete
Factory Tooling & Handling Equipment Design
Tooling & Handling Equipment Fabrication
Component Fabrication Preliminary Design Review
MRPII Detail Activation
MRPII Assembly Activation
Factory Integration
Monthly Delivery
- - 1 2 2
Cumulative Delivery
- - 1 3 5
Reliability and Maintainability Demo Units 1-
On-site Integration an
J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J
FY 1997
FY 1998
FY 1999
FY 2000
FY 2001
1997
1998
1999
2000
200



12 12 12 12 10 12 12 12 12 12 12 12 12 12 12 12 12 12 10 12 12 12 12 12 12 12 11
138 150 162 172 184 196 208 220 232 244 256 268 280 292 304 314 326 338 350 362 374 386 398 409
Production (3) Cavity Cryomodule
2 2 1 2 2 2 2 2 2 2 2
12 14 15 17 19 21 23 25 27 29 31
Ramp-up (4) Cavity Cryomodule
- 1 - 1 1 1 2 2 2
- 1 - 2 3 4 6 8 10
Production (4) Cavity Cryomodule
Monthly Delivery
4 4 4 3 4 4 4 4 4 4 4 4 4 4 4 4 3 4 3
Cumulative Delivery
14 18 22 25 29 33 37 41 45 49 53 57 61 65 69 72 76 79
Installation
Test with RF
On-Site Integration Units 8-234
Monthly Delivery
8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 3
Cumulative Delivery
15 23 31 39 47 55 63 71 79 87 95 103 111 119 127 135 143 151 159 167 175 183 191 199 207 215 223 231 234
On-Site Test Units 8-234
A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S O N D
FY 2002
FY 2003
FY 2004
FY 2005
FY 2006
FY 2007
2002
2003
2004
2005
2006

Comparison With Los Alamos' 4/3/96 SCL Schedule

A comparison of the Northrop Grumman manufacturing schedule evaluation with Los Alamos' 4/96 Integrated SCRF Accelerator Schedule for several of the critical path activities for the SCL is provided in the next chart.

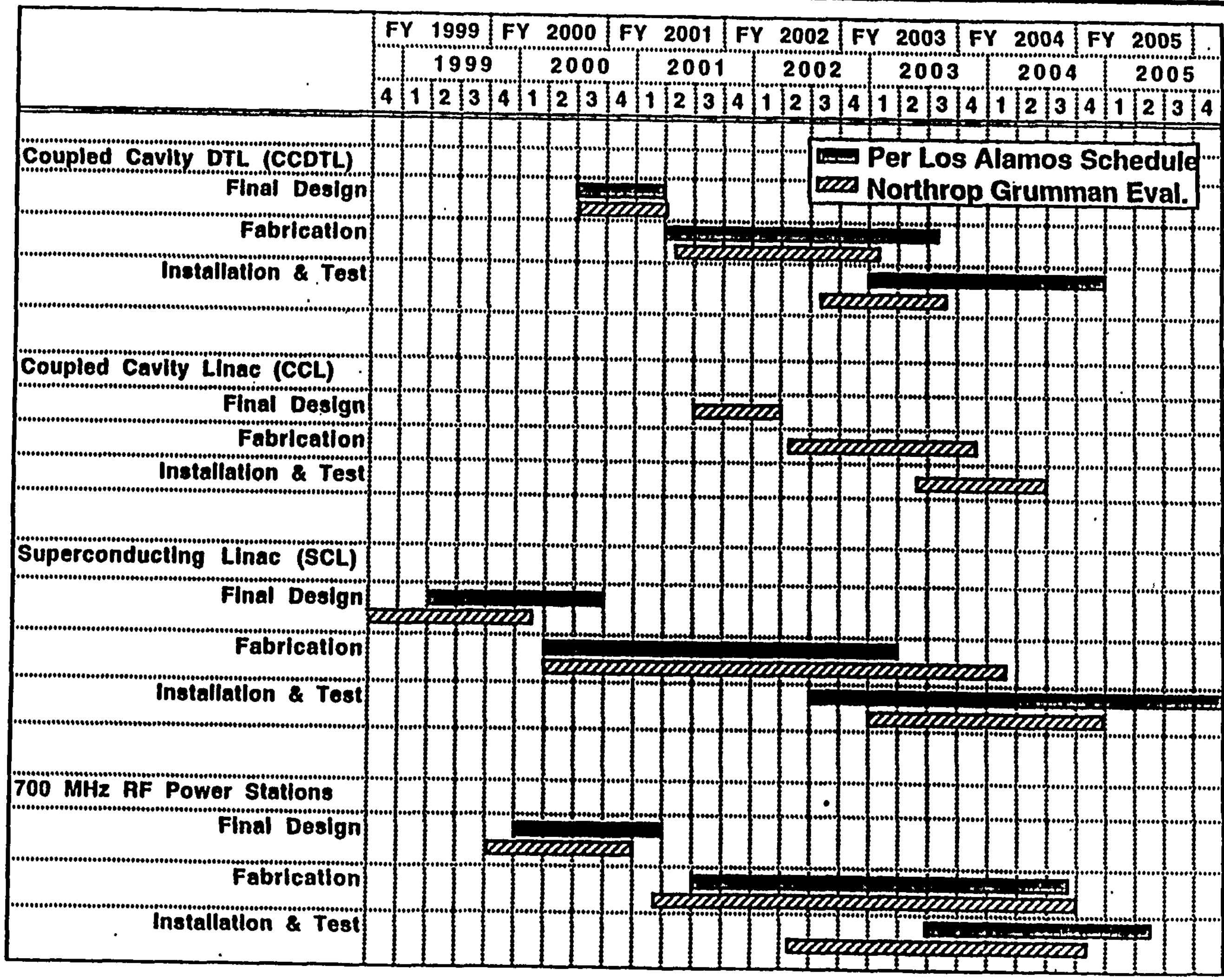
As shown, we would advance the fabrication, installation and test of the CCDTL structures so that the CCDTL and CCL can both be completed by July 2004. This modification was supported by a detailed assessment of the manufacturing flows and cycle times for both structures which includes a level loading of both personnel and key facilities such as braze furnaces. The Northrop Grumman evaluation provides slightly less than two years to install and rf test these room temperature linac sections (to 217 MeV).

The Northrop Grumman evaluation of the schedule for the superconducting linac increases the fabrication time from three years to almost four years and removes the overlap between the final design and fabrication activities (assuming final design can be initiated at the beginning of the first quarter of FY'99). Installation and test of the superconduction cryomodules occurs over a two year period which overlaps the fabrication activity by one year. This is preceded by off-line acceptance testing of each cryomodule including both full power rf testing at cryogenic operating temperatures (not shown).

The Northrop Grumman evaluation of the schedule for the rf power stations indicates a 6 month longer fabrication activity, but a net improvement in the overall schedule for this activity, which results from considerable overlap of the fabrication and installation & test activities. One key assumption is that the initial seven stations will be built and used for a RAM demonstration prior to installation at SRL. Another is that the time to complete installation of the last rf system will be one month subsequent to its delivery to the site.

It is further assumed that this station (and all of the others) can be fully integrated with the SCL cryomodules in an additional two months, after which the full energy beam test is to be initiated.

Comparison With Los Alamos' 4/3/96 SCL Schedule



2.5 Principal Conclusions & Recommendations

Although this activity is ongoing, there are several important conclusions that have been drawn from the first phase. These conclusions are summarized below:

- In comparison with the normal conducting linac, the superconducting linac is less complex and avoids rf losses in the accelerator structure. Its capital and life cycle costs are both estimated to be more than 20% lower
- Cost trades indicate that the baseline linac (100 mA, 1700 MeV) is near optimal
  - Several alternatives that were considered do not provide substantial capital or life cycle cost advantage
  - Operation at full capacity over a shorter production year appears to be the most economical strategy for reduced production requirement (e.g., ~2 kg/yr rather than the baseline 3 kg/yr)
- Cost sensitivities indicate that if the coupler power were limited to 140 kW, the penalties would be minimal (4% capital cost, 2% life cycle cost) RAM studies indicate the linac design has achieved good prospects for high availability (~85%)
  - Reasonable RAM budget allocations to all subsystems and component assemblies
  - Low sensitivity to rf tube and/or station failures because SCL can operate through failure of one or more cryomodules and because rf stations can be repaired on-line, during plant operation
- The linac RAM performance is sensitive to the achievable failure rate of the ~ 800 RF window/coupler assemblies. The linac can operate through the failure of a limited number of windows, but they can not be repaired on-line
- If desired, the cost of additional linac capability to provide a RAM hedge will be low (< $60 M for 10% hedge)
- Assuming success oriented integration and test, the program schedule appears to be conservative

3.0 Task 1: ASM Models For APT Baseline Linacs

At the inception of this contract effort, Los Alamos had developed "then-current" APT linac configurations based upon normal conducting technologies below 217 MeV and either normal or superconducting rf linac technologies for the high energy linac above 217 MeV. These configurations, as they existed on 6 August 1996, were used as the "baselines" for Task 1. The one exception was a change from six cavities per cryostat to 3 cavities per cryostat in the medium-ß supercondicting accelertor that was made on 14 August. Although there have been other minor modifications to the superconducting configuration since that time, the current design is similar enough to the baseline design that the trends identified in this study should be equally applicable.

The Accelerator Systems Model (ASM) is briefly described in Section 3.1. The modeling results, as they apply to the above baseline superconducting and normal conducting linac configurations, cost and reliability/availability/maintainability (RAM) characteristics of the APT baseline linacs are presented in Sections 3.2, 3.3, and 3.4, respectively.

3.1 The Accelerator Systems Model (ASM)

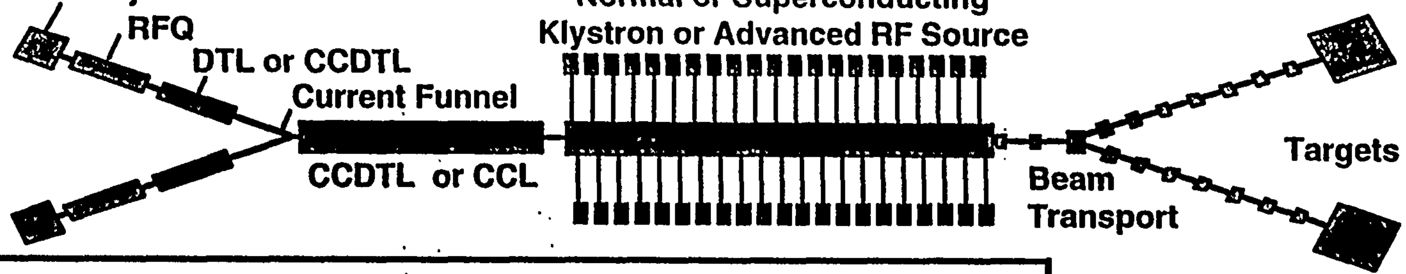
The Accelerator Systems Model (ASM), developed by Northrop Grumman in cooperation with G. H. Gillespie Associates and Los Alamos during the past four years, was used extensively in the performance of Tasks 1 and 2 of the *Assessment Of Alternative RF Linac Structures For APT* study, the results of which are summarized in this section. ASM provides the following unique capabilities for detailed layout and system-level evaluation of advanced rf linacs:

- Ability to model ion linac configurations based upon a large number of existing and recently proposed normal and superconducting linac structures, operating over a wide range of rf frequencies
- Detailed cell-by-cell tracking of the linac configuration and the electrical and rf power system performance
- Generation of detailed component inventory that includes all linac systems and dedicated facilities
- System reliability, availability, maintainability (RAM) modeling for estimation of operational availability and the cost of component replacement and/or refurbishment
- Cost analysis capability which encompasses capital, construction, and annual operating costs, resulting in a single life cycle cost estimate

As indicated on the following two charts, the current version of ASM, includes specific models for all of the accelerating structures in the APT designs, allowing the analyst to consider many linac configurations and technology trades using a consistent set of modeling algorithms.

The on-going ASM development effort is currently concentrating on the improvement of existing models (e.g., diagnostics, instrumentation and control and cryogenics), implementation of an automated capability for parameter trades, and adaptation of the code for pulsed ion linacs. Future ASM variants dedicated to applications involving electron beam linacs, free electron lasers, ion cyclotrons and ion storage rings are envisaged.

Accelerator Systems Model (ASM*) Used To Perform Study



Existing Models:

• Ion Sources	- ECR or RF-Driven
• LEBTs	- PMQ or EMS
• RFQ's	- Conv. or Resonantly Coupled
• Matching	- Interstructure & Funnel
• DTL	- Various Lattices & Magnet Types
• CCDTL	- 2 or 3 Gaps
• CCL	- Individual Tanks or RF Supermodule
• SCL	- Low β Independent Cavities or High β Multi-Elliptical Cell Cavities
• HEBT	- Per User Specified Layout
• RF Power	- Complete Station Incl. Output/Driver Tubes, Power Supplies, Transport
• Services	- Thermal (Incl. , Cryoplant), Elec., I&C
• Dedicated Facilities	- Tunnel, Buildings
• Cost	- Life Cycle Incl. Labor, Materials, Learning Curves, Elec., Staff, Replacements, etc.
• RAM	- Requirements Allocation & Sensitivities

* ASM is a joint development of Northrop Grumman, G.H. Gillespie Assoc., and Los Alamos

ASM Calculational Flow

Inputs
- Global requirements (energy, current, freq., mass, charge)
- Linac RF structures & config.
- Physics recipes
- RF power tech. & config.
- Engineering, RAM, cost data
- Energy break points/other logic

Beamline Physics Layout
- Injector & RFQ sizing & performance
- Matching between accelerating structures
- Cell-by-cell lattice & magnet requirements
- Cell-by-cell electric field ramping & power consumption
- Tanking break points
- Beamline power & parts inventory buildup

RF Power Sizing
- Selection & sizing of 2-3 stage RF amplifier chain
- RF configuration (AC line to linac cavity)
- Determination of AC power requirements

RAM Estimation
- Equipment failure rates & times to repair or replace
- Subsystem reliability/availability/ maintainability (RAM) buildups (including spares)
- System reliability & availability estimation

Linac / RF System Cost
- Non-recurring engineering cost
- Unit manufacturing costs for major components & assemblies
- Scaling for size & quantity
- Building & facility costs
- Operating costs (staff, elec., replacements)
- Discounted present value of life cycle cost

Summary
- Cell & tank details
- Linac layout
- RF & power flow
- Reliability & availability
- Capital & operating costs
- Manufacturing Schedule
- Life cycle costs

3.2 APT Linac Configuration Modeling

ASM models for the baseline normal and superconducting APT linacs were developed as a basis for establishing the relative performance and cost of these two technology alternatives, and as a basis for the subsequent trade studies reported in Section 4. The modeling goals were to generate cell-by-cell linac configurations that matched the Los Alamos-provided design in key areas such as the number, lengths and energies of the various accelerating structures as well as the rf and electrical power requirements of those structures. The derived data was then used to develop the capital costs of the linac and to size and configure the RF power system, whose cost was also estimated by the code. By keeping close track of the component inventory, it was also possible to develop high fidelity models for RAM performance.

This section describes the results of ASM configuration modeling for the baseline normal and superconducting APT linacs. ASM cost and RAM results for these linac configurations are presented in Sections 3.3 and 3.4.

3.2.1 Ground Rules & Assumptions

The "baseline" configurations for the normal conducting and superconducting linac (NCL and SCL) technology alternatives were modeled as follows:

- NCL for ~2 kg/yr production (100 mA, 1300 MeV, 2.13 kg/yr @75% duty factor))
- Upgraded NCL for ~3 kg/yr production (136 mA, 1300 MeV, 2.90 kg/yr @75% duty factor). This is same high energy linac with beam funnel at 20 MeV and additional rf power stations to accomidate increased beam current)
- Dual production level SCL for ~2 kg/yr (100 mA, 1340 MeV, 2.20 kg/yr @75% duty factor operated with 140 kW per RF power coupler in high beta section) or ~3 kg/yr (100 mA, 1780 MeV, 3.15 kg/yr @75% duty factor opeated with maximum 210 kW per RF power coupler).

The linac structure below 217 MeV was normal conducting and identical in all three cases. [Consideration of detailed matching at 217 MeV between the CCL and the medium beta superconducting structure would invalidate this assumption, but the effect is expected to be negligable from a system perspective.]

Where the tritium production level is ~2 kg/yr, it is assumed that a tritium breeding safety factor of ~10% is held back and is not included in the production rate or integrated capacity. Where the tritium production level is 3 kg/yr, the additional production associated with the safety factor is included, so the required production is less than a factor of 1.5 higher. This accounts for the upgraded parameters of 136 mA (NCL upgrade) and 1780 MeV (SCL maximum capability) above.

All of the RF power stations are based upon modulated anode klystron technology, rated at 1000 kW each, delivering up to 840 kW to the linac cavities.

3.2.2 Normal Conducting Linac Baseline Configuration

This section describes the ASM physics layout and machine configuration of the baseline normal conducting linac. The ASM results are compared with the point design information provided by Los Alamos.

3.2.2.1 Los Alamos' Normal Conducting Configuration (~2 kg/yr)

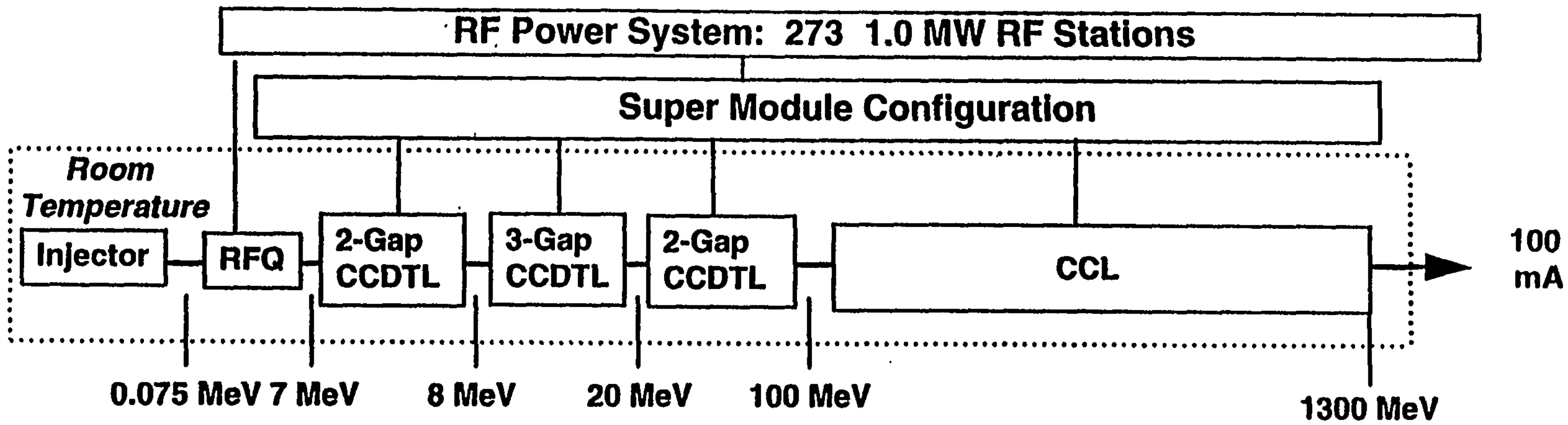
The normal conducting linac configuration for APT is shown on the next page. It is based upon an evolution of the technology used in the Los Alamos Meson Production Facility (LAMPF), extrapolated to high current CW operation involving about 100 times the average current. Like LAMPF, the APT linac would utilize a klystron-driven coupled cavity linac (CCL) over most of the energy range. However, the current design includes numerous improvements. Notable among these is the requirement to design for CW operation, which imposes new requirements such as improved cooling for higher heat loads throughout the machine, a larger beam bore, and more careful matching between linac structures to minimize beam loss and consequent activation of the linac and its surroundings.

In addition, there are several improvements in the low energy acccelerator. The first of these is the microwave ion source, which has recently demonstrated production of the goal current (about 120 mA) in CW operation over an extended period. The second improvement is a high energy (6.7 MeV) RF quadrupole (RFQ) linac which replaces the Van De Graff linac used in LAMPF. The resonantly coupled RFQ is more compact and reliable while providing more beam current of lower emittance than previous solutions. The third improvement is the coupled cavity drift tube linac (CCDTL), which replaces the Alverez-type DTL used in LAMPF. The CCDTL is less complex and expensive than the DTL, (especially its internal alignment), while also providing a higher shunt impedance in the energy range of interest.

3.2.2.1 Los Alamos' Normal Conducting Configuration (~2 kg/yr) (Continued)

A final improvewment involves the use of an RF "supermodule configuration" to add redundancy and eliminate single point failures on the RF side of the linac that would otherwise result in system shutdown. A typical supermodule involves seven 1 MW, 700 MHz RF power stations which are configured, using the linac structure as a combiner, so that full current operation requires only six of the seven stations to operate. If a station fails (e.g., if the high power klystron or its driver must be serviced) it can be decoupled from the load, serviced off-line while the system continues to operate. Since the time to repair is generally much less than the expected time between failures, the supermodule eliminates RF station failure as a first order RAM consideration.

Los Alamos' Baseline Normal Conducting APT Linac - 7/96



Final Energy	1300 MeV
Current	100 mA
Production Rate	. 2 kg/yr
Length	1182 m
RF Power	191 MW

3.2.2.2 Normal Conducting Linac Layout

In this section we compare the ASM configuration model for the baseline normal conducting linac with Los Alamos' design configuration.

To begin, we note that the ASM model for this system requires a different number of CCDTL and CCL sections than indicated in the Los Alamos design information. There are two reasons for this. First, we have modeled the the 6.7 - 8 MeV CCDTL (one drift tube per cavity) together with the and 8 - 20 MeV CCDTL (two drift tubes per cavity) as a single two drift tube structure. This was done for ASM modeling convenience. To correctly model the first CCDTL section within the ASM generated configuration, the ASM cost model (not physics) must be modified to allow a second single tube structure (the 20 - 100 MeV CCDTL) to be introduced later in the calculational flow. The required modification is, of course, possible. However, it was not given a high priority because treatment of the small 6.7 - 8 MeV CCDTL in the code has a negligable effect from the system perspective.

The second reason for a different number of CCDTL and CCL sections compared with the Los Alamos information is that ASM requires a new model element when ever the bore size of a given accelerating structure changes. As indicated in the figure at the lower left corner of the next page, the bore changes twice between 20 and 99.6 MeV, so three ASM CCDTLs are required to cover this range. Similarly, the bore changes once between 99.6 and 1300 MeV, so two ASM CCLs are required to cover this range.

Baseline Normal Conducting Linac Configuration Model

Los Alamos Normal Conducting Baseline Provided On 6 August

INJ — RFQ — CCDTL — CCDTL — CCDTL — CCL — CCL

75 KeV, 6.7 MeV, 8 MeV, 20 MeV, 99.6 MeV, 155 MeV, 1300.4 MeV

ASM Configuration Used To Model The Normal Conducting Baseline

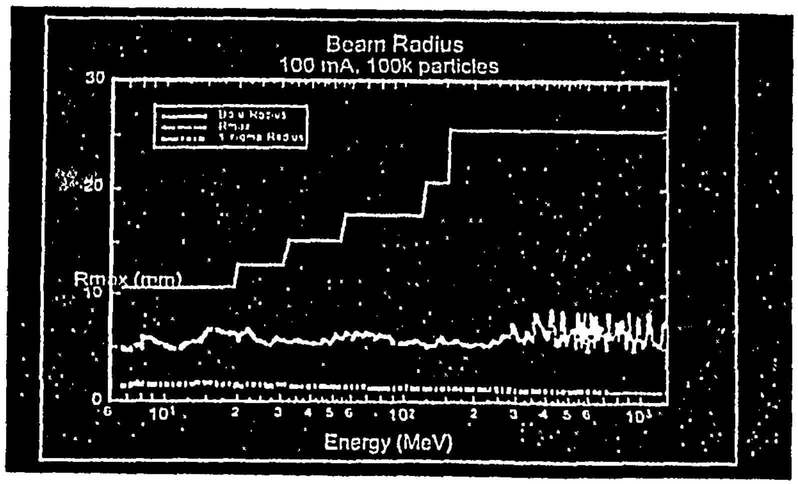
INJ — RFQ — CCDTL — CCDTL — CCDTL — CCDTL —

75 KeV, 6.7 MeV, 20 MeV, 31.1 MeV, 57.8 MeV, 99.7 MeV

— CCL — CCL — CCL —

125.2 MeV, 155.1 MeV, 1300.5 MeV

Figure 6.2.28 From Draft CDR Report



Note: ASM requires different CCDTL configuration than Los Alamos design information because:

- **Having two single drift tube CCDTL sections seperated by a single drift tube section is prohibited by ASM's cost estimation logic**
- **ASM requires a new model element whenever the bore size of the accelerating structure changes**

Comments On ASM CCDTL Models

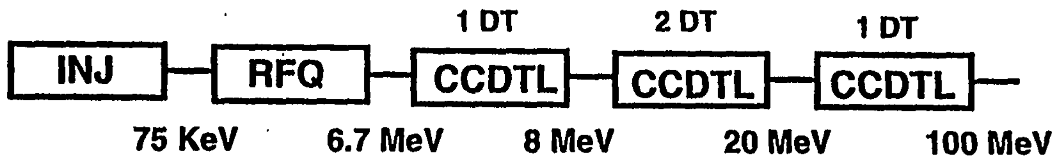
The implications of the CCDTL modeling approximation highlighted in the previous chart were investigated in detail. The two ASM physics/configuration models shown on the next page were used. The first model (ASM1) includes all of the features of the Los Alamos design. The second model (ASM2) lumps the first two CCDTL's.

The following two pages depict the ASM results for each of these models. As shown, with the exception of a 0.5 m (0.5%) difference in the total CCDTL length and a 1.9% difference in the power consumption the ASM 1 model is in near perfect agreement with the design. The ASM 2 model results in a slightly larger discrepancy in the CCDTL length (1.7%) and a 2.4% difference in the power.

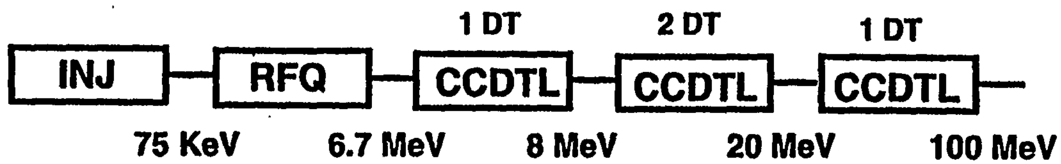
The conclusion to be drawn is that the ASM 2 model, which was used in the costing analysis, is of sufficient fidelity to provide an excellent representation of the design.

CCDTL Modeling Approximation

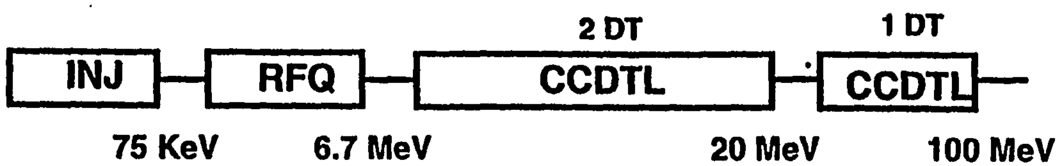
Los Alamos Normal Conducting Baseline CCDTL Configuration



ASM Model 1: (Full Representation Of Los Alamos Front End)



ASM Model 2: (Modeling Simplification Eliminates 6.7 - 8 MeV CCDTL)



CCDTL Modeling Results

Parameter	CCDTL I	CCDTL II	CCDTL III	Totals
Final Energy (MeV)				
Los Alamos	8.0	20.0	99.6	---
ASM 1	8.0	20.0	99.6	---
ASM 2	N/A	20.0	99.7	---
Accel. Gaps/Cavity				
Los Alamos	2	3	2	---
ASM 1	2	3	2	---
ASM 2	N/A	3	2	---
No. Of Cavities				
Los Alamos	24	59	150	233
ASM 1	24	59	150	233
ASM 2	N/A	83	150	233
Total No. Of Gaps				
Los Alamos	48	177	300	525
ASM 1	48	177	300	525
ASM 2	N/A	249	300	549

CCDTL Modeling Results (cont'd)

Parameter	CCDTL I	CCDTL II	CCDTL III	Totals
Section Length (m)				
Los Alamos	5.1	16.5	81.4	103.0
ASM 1	5.1	16.4	82.0	103.5
ASM 2	N/A	22.8	81.9	104.7
Section Power (MW)				
Los Alamos	----	----	----	13.92
ASM 1	0.29	1.91	11.99	14.19
ASM 2	N/A	2.23	12.03	14.26

3.2.2.3 RF Supermodule Layout

The supermodule layouts as specified by the Los Alamos design and the ASM models are shown in the next five pages. For each supermodule the energy breaks, beam and structure powers, RF station allocation, and RF station power requirements are shown. As indicated, the estimated values agree to within <1%.

It should be noted that the total number of RF power stations indicated in the table represents the operational requirement and does not include the one spare RF station for each supermodule. Therefore, the total number of RF power stations for the normal conducting design will be 227 + 43 = 270, representing 270 MW of installed RF power and providing 227 * 0.833 (average) = 189 MW of RF power to the rf linac cavities.

Normal Conducting Linac Supermodule Layout

Number	E [MeV]	P_{BEAM}	P_{STRUCT}	Total	RF Stations	Power/Sta.	
1	16.52	0.98	0.70	1.68	2	840	Los Alamos*
	16.50	0.98	0.70	1.68	2	840	ASM
2	44.75	2.82	1.42	4.24	5	848	Los Alamos
	44.69	2.82	1.30	4.12	5	824	ASM
3	78.69	3.39	1.71	5.10	6	850	Los Alamos
	78.61	3.39	1.71	5.10	6	850	ASM
4	110.66	3.20	1.81	5.01	6	835	Los Alamos
	110.77	3.22	1.91	5.13	6	855	ASM
5	131.45	2.08	1.25	3.33	4	833	Los Alamos
	131.46	2.07	1.27	3.34	4	835	ASM
6	152.43	2.10	1.30	3.40	4	850	Los Alamos
	152.17	2.08	1.31	3.39	4	848	ASM
7	173.61	2.12	1.26	3.38	4	845	Los Alamos
	173.70	2.11	1.26	3.37	4	843	ASM
8	194.76	2.12	1.20	3.32	4	830	Los Alamos
	194.49	2.12	1.25	3.37	4	843	ASM
9	216.81	2.21	1.20	3.41	4	853	Los Alamos
	216.54	2.21	1.18	3.39	4	848	ASM
10	238.55	2.17	1.15	3.32	4	830	Los Alamos
	238.28	2.17	1.14	3.31	4	828	ASM

* Draft APT Accelerator Conceptuual Design Report (July, 1996)

Normal Conducting Linac Supermodule Layout (cont'd)

Number	E [MeV]	P_{BEAM}	P_{STRUCT}	Total	RF Stations	Power/Sta.	
11	265.82	2.73	1.40	4.12	5	824	Los Alamos
	265.56	2.74	1.40	4.14	5	828	ASM
12	294.09	2.83	1.41	4.23	5	846	Los Alamos
	293.84	2.82	1.42	4.24	5	848	ASM
13	322.00	2.79	1.36	4.15	5	830	Los Alamos
	321.75	2.79	1.37	4.16	5	832	ASM
14	350.69	2.87	1.37	4.24	5	848	Los Alamos
	350.45	2.87	1.38	4.25	5	850	ASM
15	378.78	2.81	1.32	4.13	5	826	Los Alamos
	378.54	2.81	1.33	4.14	5	828	ASM
16	407.49	2.87	1.33	4.21	5	842	Los Alamos
	407.26	2.87	1.34	4.21	5	842	ASM
17	435.39	2.79	1.28	4.07	5	814	Los Alamos
	435.17	2.79	1.29	4.08	5	816	ASM
18	463.79	2.84	1.29	4.13	5	826	Los Alamos
	463.58	2.84	1.29	4.13	5	826	ASM
19	492.67	2.89	1.30	4.19	5	838	Los Alamos
	492.46	2.89	1.29	4.18	5	836	ASM
20	521.99	2.93	1.31	4.25	5	830	Los Alamos
	521.80	2.93	1.29	4.22	5	844	ASM

Normal Conducting Linac Supermodule Layout (cont'd)

Number	E [MeV]	P_{BEAM}	P_{STRUCT}	Total	RF Stations	Power/Sta.	
21	550.24	2.82	1.26	4.08	5	816	Los Alamos
	550.05	2.83	1.26	4.09	5	818	ASM
22	578.85	2.86	1.27	4.13	5	826	Los Alamos
	578.67	2.86	1.22	4.08	5	816	ASM
23	607.79	2.89	1.28	4.17	5	834	Los Alamos
	607.62	2.90	1.23	4.13	5	826	ASM
24	637.06	2.93	1.28	4.21	5	842	Los Alamos
	636.89	2.93	1.25	4.18	5	836	ASM
25	671.32	3.43	1.50	4.92	6	820	Los Alamos
	671.17	3.45	1.46	4.91	6	818	ASM
26	705.96	3.46	1.51	4.97	6	828	Los Alamos
	705.82	3.47	1.48	4.95	6	825	ASM
27	740.96	3.50	1.52	5.02	6	837	Los Alamos
	740.83	3.50	1.49	4.99	6	832	ASM
28	776.29	3.53	1.53	5.06	6	843	Los Alamos
	776.17	3.54	1.51	5.05	6	842	ASM
29	811.93	3.56	1.54	5.10	6	850	Los Alamos
	811.83	3.57	1.52	5.09	6	848	ASM
30	846.24	3.43	1.48	4.91	6	818	Los Alamos
	846.14	3.43	1.46	4.89	6	815	ASM

Normal Conducting Linac Supermodule Layout (cont'd)

Number	E [MeV]	P_{BEAM}	P_{STRUCT}	Total	RF Stations	Power/Sta.	
31	880.79 880.71	3.46 3.46	1.48 1.47	4.94 4.93	6 6	823 822	Los Alamos ASM
32	915.59 915.51	3.48 3.48	1.49 1.51	4.97 4.99	6 6	828 832	Los Alamos ASM
33	950.61 950.55	3.50 3.50	1.50 1.49	5.00 4.99	6 6	833 832	Los Alamos ASM
34	985.84 985.79	3.52 3.52	1.51 1.50	5.03 5.02	6 6	838 837	Los Alamos ASM
35	1021.28 1021.24	3.54 3.55	1.51 1.51	5.05 5.06	6 6	843 843	Los Alamos ASM
36	1056.91 1056.89	3.56 3.57	1.52 1.52	5.08 5.09	6 6	847 848	Los Alamos ASM
37	1092.73 1092.71	3.58 3.58	1.53 1.53	5.11 5.11	6 6	852 852	Los Alamos ASM
38	1128.71 1128.71	3.60 3.60	1.53 1.53	5.13 5.13	6 6	855 855	Los Alamos ASM
39	1163.13 1163.14	3.44 3.44	1.46 1.47	4.91 4.91	6 6	818 818	Los Alamos ASM
40	1197.70 1197.71	3.46 3.46	1.47 1.47	4.92 4.93	6 6	820 822	Los Alamos ASM

Normal Conducting Linac Supermodule Layout (cont'd)

Number	E [MeV]	P_{BEAM}	P_{STRUCT}	Total	RF Stations	Power/Sta.	
41	1232.40	3.47	1.47	4.94	6	823	Los Alamos
	1232.40	3.47	1.48	4.95	6	825	ASM
42	1267.22	3.48	1.48	4.96	6	827	Los Alamos
	1267.26	3.48	1.48	4.96	6	827	ASM
43	1300.42	3.32	1.41	4.73	6	788	Los Alamos
	1300.47	3.32	1.41	4.73	6	788	ASM
Totals	--------	129.37	59.89	189.26	227	834	Los Alamos
	--------	129.43	59.68	189.11	227	833	ASM

3.2.2.4 NCL Configuration Modeling Summary (~2 kg/yr)

The configuration modeling results for the 2 kg/yr normal conducting baseline design are summarized on the next page. The table shows, for each linac section, the energy break points, the number of RF cavities, the length of the section and the RF power input to the cavity (as opposed to output from the tubes which includes transmission losses and design margins and is about 20% higher).

As indicated, all of these quantities are in close agreement with the detailed design. The reader should recall that ASM CCDTL II includes CCDTL I, so that its results compare with the sum of both structures in the Los Alamos Design.

APT Normal Conducting Linac Baseline Model Results

	INJ	RFQ	CCDTL I	CCDTL II	CCDTL III	CCL I	CCL II	Totals
Final Energy (MeV)								
Los Alamos*	.075	6.70	8.0	20.0	99.6	155.0	1300.4	1300.4
ASM	.075	6.73	----	20.0	99.7	155.1	1300.5	1300.5
No. Of Cavities								
Los Alamos	-----	------	24	59	150	63	763	1059
ASM	-----	------	----	83	150	63	763	1059
Section Length (m)								
Los Alamos	2.8	8.0	5.1	16.5	81.4	50.9	1017.7	1182.4
ASM	2.8	8.0	----	22.8	81.9	50.8	1017.5	1183.8
RF Power (MW)								
Los Alamos	-----	1.96	===>	===>	13.92	===>	175.3	191.18
ASM	-----	1.96	-----	2.23	12.03	===>	174.85	191.07

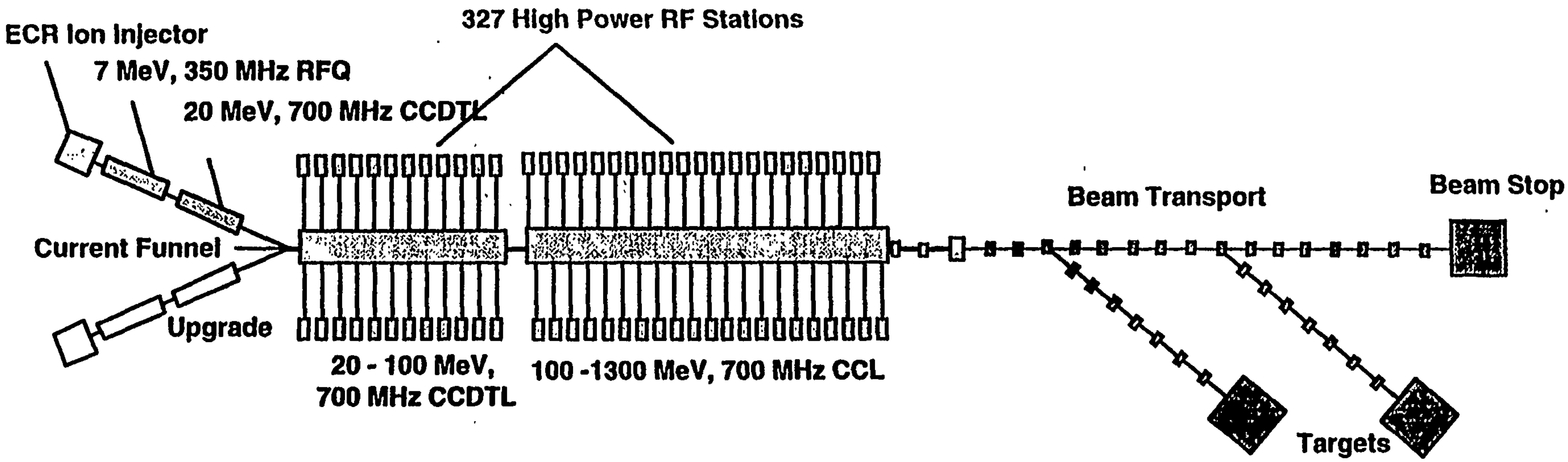
* Draft APT Accelerator Conceptuual Design Report (July, 1996)

3.2.2.5 Normal Conducting Linac Upgrade Configuration (3 kg/yr)

Upgrading the normal conducting APT linac from ~2 kg/yr to ~3 kg/yr would be accomplished by adding a parallel beamline, then funneling the two beamlines into a single beamline at 20 MeV. The baseline ~2 kg/yr configuration anticipates this as a possible requirement by doubling the RF frequency after the RFQ. Therefore the two 350 MHz RFQs, each of which fills half of the available rf buckets at 700 MHz, would be synchronized to fill all of the rf buckets after 20 MeV in the subsequent structure, which operates at 700 MHz. [Note that the reason that the CCDTLs below 20 MeV operate at 700 MHz primarily involves fabrication difficulties at 350 MHz (twice the diameter) rather than beam dynamics requirements. Nevertheless, this selection should simplify the 20 MeV beam funnel].

As noted earlier, the beam current requirement for the upgrade is 136 mA, so each of the two low energy beamlines must produce 68 mA. The acceleration of 36 additional milliamps of current to 1300 MeV requires that additional RF power stations and RF transport lines be added down the entire length of the linac (with appropriate replumbing of RF couplers, etc.). In other respects the ~2 and 3 kg/yr normal conducting beamlines are identical. The major considerations for upgrading of the normal conducting linac from ~2 to ~3 kg/yr, as modeled by ASM, are indicated on the next page.

Upgrading The Normal Conducting Linac For 3 Kg/yr



Production	Beam Current	RF Power	No. RF Stations
2 kg/yr	100 mA	191 MW	273
3 kg/yr	67/134 mA	238 MW	339

3.2.3 Superconducting Linac Baseline Configuration

The baseline superconducting linac configuration described in this section draws upon recent advancements in electron linac technology that have been established at TJNAF, CERN and elsewhere. Although it would be the first superconducting proton linac, the really new features are its acceleration of a high ion current (100 mA) beam, beginning at about half the velocity of light. The additional challenges associated with these features may be more than offset by the advantages of superconducting operation.

More specifically, the low electricity consumption and high achievable electric field of the rf superconductor allow for the practicality of both a large beam aperture and of accelerating particles of non-optimal energy through linac structures. For example, a superconducting RF structure sized to have maximum acceleration efficiency for an ion of velocity, $\beta = 0.64$ can achieve acceptable acceleration when the beam velocity is as low as $\beta = 0.58$ or as high as $\beta = 0.75$. This implies that the superconducting linac can be comprised of only a few types of identical modules (the APT superconducting baseline considered herein uses two types, a medium energy cavity [$\beta = 0.64$] and a high energy cavity [$\beta = 0.82$]) as opposed to normal conducting linac structures that vary continuously in length.

3.2.3 Superconducting Linac Baseline Configuration (cont'd)

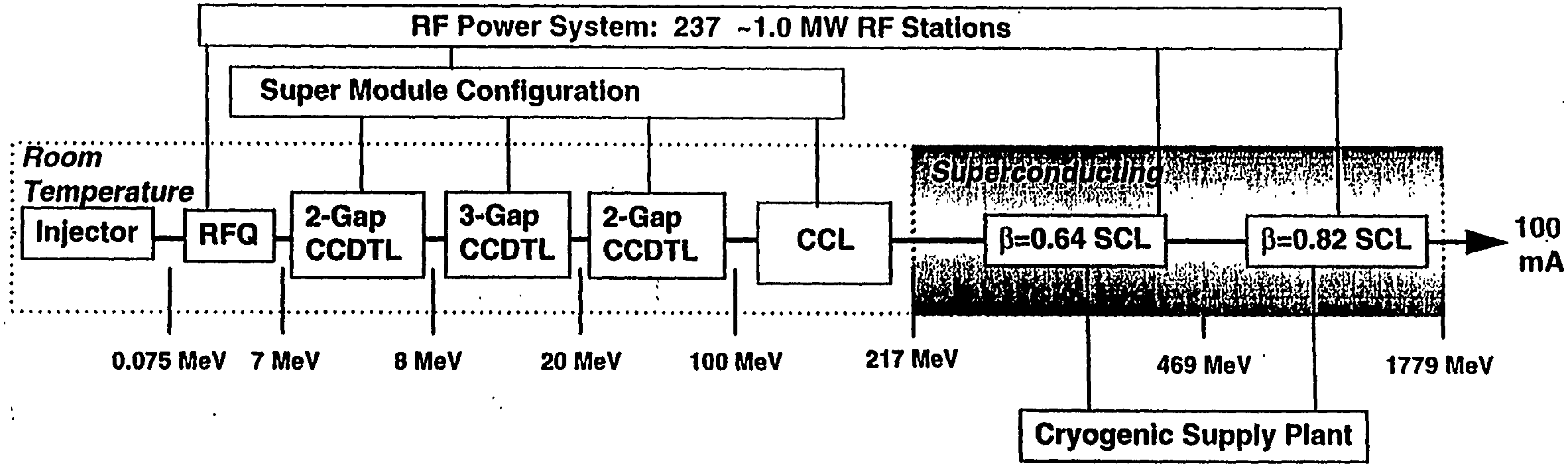
This allows for lower complexity of the superconducting linac and higher operational flexibility. For example, since the efficiency of the structure is not sensitive to the precise beam energy, if the operability of one or more accelerating cavities is interrupted, it will be possible to adjust the rf phase and amplitude in several successive cavities to recover the beam and restore it to the expected final velocity. Similarly, it will be possible to operate the same linac at two quite different final energies by changing the power input and rf electric accelerating fields in the final set of accelerating structures. The large beam aperture that can be provided reduces the sensitivity to the size of the beam halo (which could impinge on a smaller beam aperture).

All of these techniques are to be employed in the baseline superconducting linac described herein. It employs a beam aperture that is approximately 14 times the RMS radius of the beam. It is tolerant of in-line failures of one or more rf power stations, rf drive lines, cavities, etc. Depending upon the number of operable rf cavities and the power capacity of the rf drive line (containing one or more vacuum windows), the linac can produce a final energy between 1300 MeV (1340 MeV with all equipment operable) and 1700 MeV (1780 MeV with all equipment operable).

3.2.3.1 Los Alamos' SCL Baseline Configuration (2 or 3 kg/yr)

This subsection provides highlights of ther SCL baseline machine configuration that was provided by Los Alamos (shown on next page). This machine can be operated to produce up to ~3 kg/yr (3.15 kg/yr @75% duty factor) when operated at full rf power and energy (1780 MeV). Additional configuration modeling detail is provded in the subsequent subsections.

Los Alamos' Baseline Superconducting APT Linac 7/96



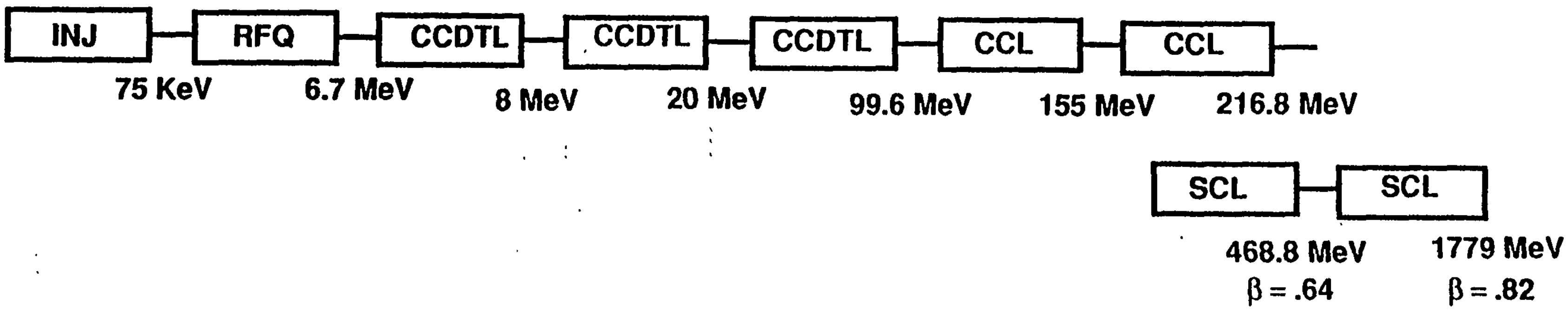
Final Energy	1780 MeV
Current	100 mA
Length	1212 m
RF Power	191 MW

3.2.3.2 ASM Superconducting Linac Layout

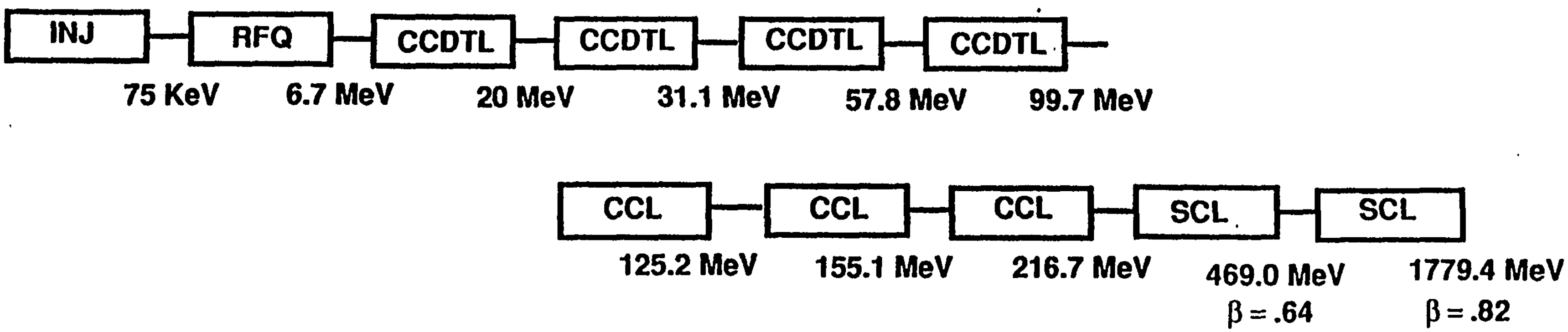
An ASM model of the superconducting linac configuration shown on the previous page was developed using the RF linac elements indicated on the next page. Up to 217 MeV, the linac is identical to the normal conducting linac described in Section 3.1.2. Beyond 217 MeV the ASM models use the same two fixed β structures as the Los Alamos design, achieving a near perfect configuration match.

Baseline ASM Superconducting Linac Configuration Model

Los Alamos Superconducting Baseline Provided On 6 August



ASM Configuration Used To Model The Superonducting Baseline



Comments On Superconducting Linac ASM Modeling Results

The ASM superconducting linac (SCL) modeling results are indicated on the next two pages. These results are, again, in close agreement with Los Alamos' design (Los Alamos results not shown here). The last row indicates the changes in machine parameters when the RF coupler power is increased from 140 kW to 210 kW.

Superconducting Linac ASM Modeling Results

Section	β_G	W (MeV)	β	N_{cells}	E_a (MeV)	E_{peak} MV/m	Apert Rad (cm)	P_{coup} (kW)	I (mA)	ΔW_{cav} (MeV)	N_{coup}	coup/cavity	cav/klystr	Erea (MeV/m)*	N_{cav}	N_{kly}	L_{tot}* (m)	P_{kly} (kW)	P_{cryo} (kW)
Med beta	0.64	217.0 - 469.0	.583 - .745	5	4.99 - 5.34	N/A	6.5	140.00	100	2.80	180	2	3	1.24	90	30	204.0	840.0	2.04
High beta	0.82	469.0 - 1342.4	.745 - .911	5	3.89 - 4.31	N/A	8.0	140.00	100	2.80	624	2	2	1.10	312	156	791.7	559.9	5.84
High beta up-grade	0.82	469.0 - 1779.4	.745 - .939	5	5.84 - 6.06	N/A	8.0	210.00	100	4.20	624	2	2	1.66	312	156	791.7	840.0	9.04

Superconducting Linac ASM Modeling Results (cont'd)

Sect-ion	β_G	W (MeV)	Ncav/ Cryo	N_{cryo} stats	Bpeak Gauss	G (T/m)	Lq (m)	L(m) half period	$\sigma t0$ (deg)	$\sigma l0$ (deg)	ϕ (deg)	$\Delta W^* \tan(\phi)/L$
Med beta	0.64	217.0 - 469.0	3	30	N/A	N/A	.305	1.7	80 - 80	40.7 - 23.9	35	N/A
High beta	0.82	469.0 - 1342.4	4	78	N/A	N/A	.459	2.035	80 - 80	28.0 - 8.4	35	N/A
High beta up-grade	0.82	469.0 - 1779.4	4	78	N/A	N/A	.459	2.030	80 - 80	28.0 - 8.4	35	N/A

3.2.3.3 Configuration Modeling Summary For SCL

The configuration modeling results for the superconducting baseline design are summarized on the next page. The table shows, for each linac section, the energy break points, the number of RF cavities, the length of the section, the RF power requirement, the number of rf stations and the cryogenic heat load. The ASM models are in close agreement with Los Alamos' design results.

Summary Of Results For APT SCL Baseline

	INJ	RFQ	CCDTL	CCL	SCL I	SCL II	Totals
Final Energy (MeV)							
LANL CDR	.075	6.70	99.6	216.8	468.0	1779.0	1779.0
ASM	.075	6.73	99.7	216.7	469.0	1779.4	1779.4
No. Of Cavities							
LANL CDR	-----	------	233	120	90	312	---------
ASM	-----	------	233	120	90	312	---------
Section Length (m)							
LANL CDR	2.8	8.0	103.0	104.5	204.0	791.7	1211.5
ASM	2.8	8.0	104.7	104.4	204.0	791.7	1215.6
RF Power (MW)							
LANL CDR	-----	1.96	13.92	18.94	25.20	131.04	191.06
ASM	-----	1.96	14.26	18.55	25.20	131.04	191.01
No. Klystrons							
LANL CDR	-------	3	16	23	30	156	228
ASM	-------	3	16	23	30	156	228
Cryo Heat Load (kW)							
LANL CDR	--------	--------	---------	----------	2.04	8.93	10.97
ASM	--------	--------	---------	----------	2.04	9.04	11.08

3.3 Cost Comparison Of Normal And Superconducting Linacs

ASM cost estimates for the APT plant, based upon the baseline normal conducting and superconducting APT linacs discussed in Section 3.2, are reported in this section. The relative capital, operating and life-cycle costs of these two technology alternatives are provided.

The development of the estimates reported herein was preceded by an activity which compared our ASM results for the cost of the APT linac with a Los Alamos cost estimate for the September 1995 superconducting linac design (100 mA, 1000 MeV). [LA-UR-95-4045: "A Feasibility Study of the APT Superconducting Linac, 1995", dated April 1996.] This analysis is provided as Appendix B, *ASM Cost Benchmarking Against Previous APT Cost Estimate.*] Given the differences in organization of the cost accounts, and the differences in assumptions on procurement (i.e.., whether or not an item would be made in-house [therefore accounted as *labor*] or purchased [and accounted as *materials*]), the results of this comparison, indicate acceptable agreement. Of special note, the ASM total capital cost estimate was within 14% of the previous Los Alamos estimate.

3.3.1 Highlights Of Cost Estimation Approach

Highlights of the cost estimating approach are provided in the next two charts. The "overnight capital cost" is comprised of all of the sum of the plant equipment, labor and materials costs from Preliminary Design through completion of the 1.5 year startup phase, but without consideration of escalation or other financing considerations during the life of the construction project. The overnight cost is added to a discounted sum of the operating costs over a 40 year period to establish the estimated life cycle cost (details of discounting assumptions will be provided later in this section). All costs in this section (and throughout this document) are referenced to 1995 dollars.

The capital cost estimates were developed, in priority order, from scaled actual costs of as-built hardware, vendor-supplied cost estimates and grass roots estimates which considered the costs and/or labor associated with all of the aspects of design, engineering, procurement, manufacturing and test.. Where multiple procurements of the same item were involved, learning curve scaling was used to reflect the reduced unit costs. For example, if the learning curve is 94% and the normalized cost of the first unit or lot is 1.0, then the cost of the second unit or lot is 0.94 and the cost of the fourth unit is 0.88, the cost of the eighth unit is 0.83, the cost of the sixteenth unit is 0.78, etc.

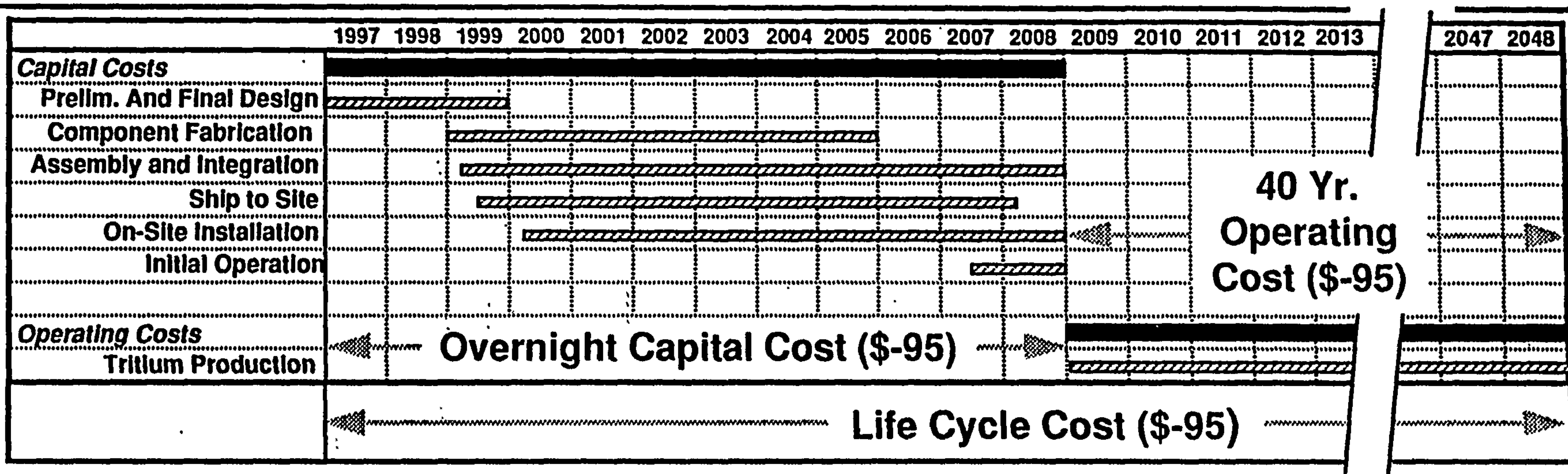
3.3.1 Highlights Of Cost Estimation Approach (Continued)

The operating costs are dominated by the cost of electricity, assumed to be 34.5 mil/kWeHr (0.0345 $/kWeHr) during the first year of operation and the cost of component replacement and refurbishment. The later cost is strongly influenced by the failure rate analysis which is embedded in the RAM analysis (see Section 2.3).

The cost analysis assumes that much of the equipment will be furnished by the government to the integrating contractor. Only the first few (Typ. 10) units would be purchased by the contractor. The net effect is to eliminate multiple procurement burdens in the procurement cycle.

The equipment budget for the linac includes contingency, which varies according to the subsystem to be procured. The analysis reported herein assumes an average contingency of 21%.

Highlights Of Cost Estimation Approach



- Capital costs developed from:
  - Scaling from similar hardware programs (e.g., RFQ)
  - Vendor cost data (e.g., superconducting cavities, RF power station)
  - Grass roots estimates and manufacturing plans (e.g., CCDTL)
  - Learning curve savings for multiple lots and rate production
- Operating costs developed from:
  - Electricity consumption (34.5 mil/kWeHr)
  - Plant staff ($73,000 per FTE)
  - Component replacement (or refurbishment) costs
- Extensive use of Government Furnished Equipment:
  - RF power equipment, vacuum pumps, focusing magnets, copper
- Average contingency = 21%

Typical Rate Production Learning Curve

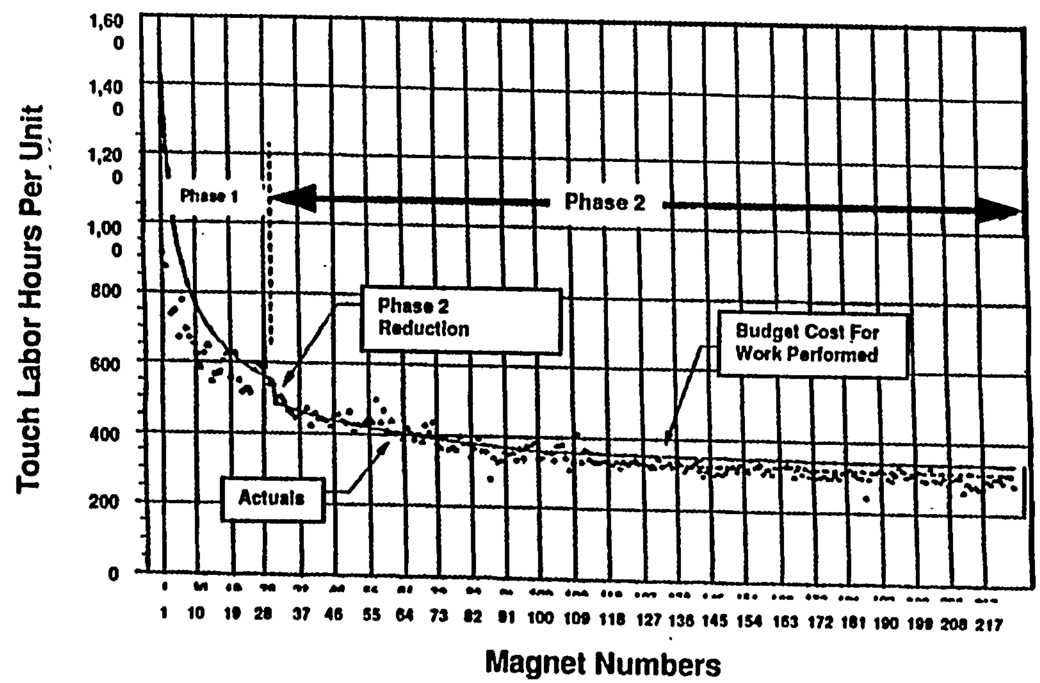
The next chart indicates typical "learning experience" in the production of high precision superconducting equipment (i.e., Northrop Grumman's production of the superconducting dipole magnets for Brookhaven's Relativistic Heavy Ion Collider, RHIC). The best fit to this experience is a 91% learning curve, which was used to estimate the production costs for the linac linac structures, both superconducting and normal conducting. A less aggressive 94% learning curve was used to estimate the rf power system components. The estimates all assume that manufacturing engineering inputs to the design process occur beginning-during Preliminary Design (cost of this activity included in the estimates) and that there will be one large production run (one manufacturer) for each major component. If the production is to be split among more than one manufacturer, then the cost will increase because the learning curve savings will be substantially reduced.

Typical Rate Production Learning Curve

- "Learning curve" equations have been used to capture reduction in estimated unit cost for large production runs
  - 94% LC for rf power systems
  - 91% LC for linac structures

- Assumptions used for APT linac:
  - Single supplier to maximize benefit (duplicate production lines will progress through same learning curve)
  - Manufacturing engineering involvement beginning during preliminary and final design phase

Example: RHIC Superconducting
<u>Dipole Magnet Production Program</u>



- 256 design changes prior to high rate production
- Touch labor range: 900 - 250 Hr (360 Ave.)
- Results in 91% learning curve

3.3.2 Capital Costs

This section describes the capital costs of APT plants based upon normal conducting and superconducting linacs.

Section 3.3.2.1 describes the basis of estimate for the cryomodules used in the superconducting linac and compares the cost of the cryomodules with the corresponding CCL structuire used in the low energy section of the superconducting linac and throughout the normal conducting linac.

Section 3.3.2.2 describes and compares the capital costs for a normal conducting linac sized for ~2 kg/yr production with the capital cost for a superconducting linac capable of up to ~3 kg/yr production. Operated at 75% plant avialability, the normal conducting APT plant (1300 MeV, 100 mA) produces 2.13 kg/yr of tritiumwhile the superconducting plant, sized for 1780 MeV, 100 mA, but operated at 1340 MeV, 100 mA, produces produces 2.20 kg/yr.

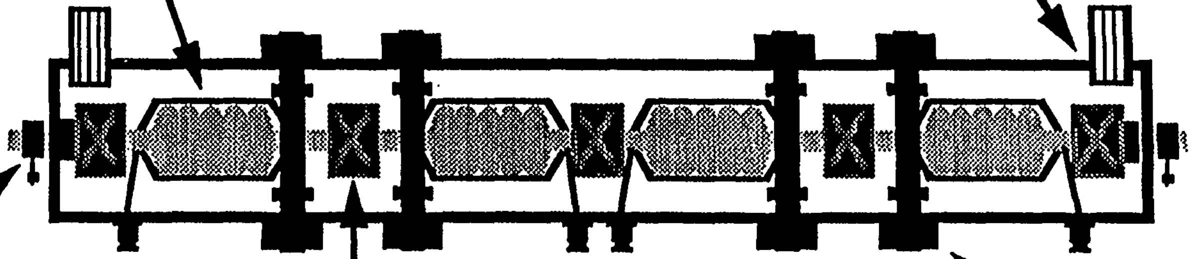
Section 3.3.2.3 describes and compares the capital cost for a more capable, current funneled, normal conducting linac (1300 MeV, 136 mA) sized for 2.90 kg/yr production at 75% availability with the capital cost for the above superconducting linac operated at 1780 MeV, 100 mA to produce 3.15 kg/yr. [Note: The capital cost of the SCL plant is the same in both cases. The operating cost, described in Section 3.3.3, increases at the higher production level.]

3.3.2.1 Cost Estimate For SCL Cryomodule

The following two charts illustrate the cost basis incorporated into ASM for the APT superconducting cryomodules. As indicated, vendor cost estimates were obtained and evaluated for nearly all of the major components that comprise the cryomodule. The exception was the rf drive line, for which a vendor estimate was not available. The cost of the drive line was separated into four components. Cost estimates for two of these, the vacuum window and the rf coupler, were developed in-house.

As indicated, our estimate for the total cost of the cryomodules, based upon a single manufacturer and a 91% learning curve is $151 M [If multiple suppliers will be required, an upwards cost adjustment will be required to reflect lower learning curve savings and additional management oversight]. The partitioning of the cost among the major components indicates that the cavities, drive lines and cryostat/cryogen distribution system each represent about about 30% of the cost and that the superconducting quadrupole magnets represent about 10% of the cryomodule cost. The average unit costs of the various cryomodule components (after learning curve savings) are shown on the right hand column of the second chart.

Cost Estimate For SCL Cryomodule - Basis Of Estimate



Accelerating Cavity Assembly
- Five accelerating cells
- De-tuner assembly
- Surrounding cryogen vessel and all flanges

Basis of Estimate:
- Vendor quotes for completed assemblies
- In-house estimate for installation labor

Cryostat & Cryogen Distribution System
- Stainless steel vessel
- Cryogen piping, valves and flanges

Basis of Estimate:
- Vendor quote for steel and "catalog" cryogenic equipment
- In-house labor estimate for fabrication of cryostat and integration of cryogen distribution equip.

Miscellaneous Parts & Final Assembly Labor
- Beam tube and flanges
- External support structure
- Flanges and other parts

Basis of Estimate:
- Vendor estimates for equipment
- In-house estimate for labor

Superconducting Focusing Magnet
- Magnet
- Power Supply
- Alignment Mechanism

Basis of Estimate:
- Vendor quote for equipment
- In-house estimate for installation labor

RF Drive Line
- 2 m section of drive line (2 m)
- Turbo pump (50 l/s)
- Vacuum window
- Cryogenically cooled rf coupler

Basis of Estimate:
- Vendor quote for "catalog" RF and vacuum equipment,
- In-house estimate for window cost
- In-house estimates for fabrication and integration labor

Cost Estimate For SCL Cryomodule - Cost Breakdown

Summary :

	Average cost ($K-95)
Medium β cryomodule (3 cavities):	$1,186
High β cryomodule (4 cavities):	$1,421

Details :

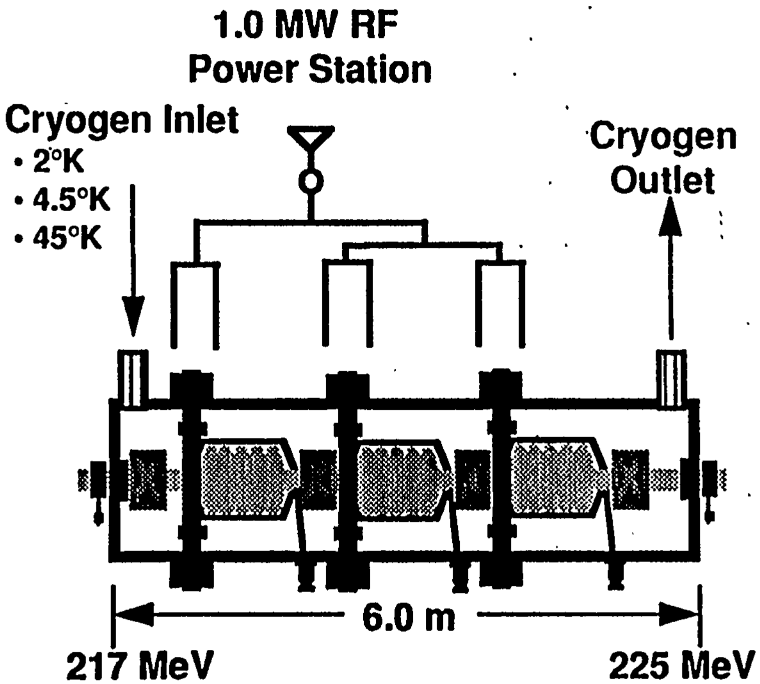
	Qty.	Costs ($M-95)			% Total	Average Cost ($k)
		Labor	Material	Total		
Final Design Mods/Production Support	1 lot	$1.6	$0.0	$2	1%	$1640
5-Cell Niobium Cavities and Cryogen Vessel	409	$12.3	$29.5	$42	28%	$102
Cryostat and Cryogen Distribution System	110	$9.8	$34.8	$45	30%	$405
Cylindrical Window	818	$0.0	$21.3	$21	14%	$26
Stub RF Drive Line	818	$1.6	$20.8	$22	15%	$27
Superconducting Magnets and P.S.	519	$1.0	$12.7	$14	9%	$26
Integration, Installation and C/O	110	$5.4	$0.0	$5	4%	$49
	Totals:	$31.6	$119.0	$151	100%	

Relative Complexity Of NCL And SCL Structures

The following chart illustrates the relative complexity of equivalent sections of the APT superconducting and normal conducting linac (SCL and NCL) designs, each of which would accelerate the beam from 217 MeV to about 226 MeV. As shown, the functional equivalent of one superconducting cryomodule (comprised of three 5 cell cavities, four superconducting quadrupole magnets and associated other components) is a section of coupled cavity linac comprised of 7 flanged segments and 7 bridge couplers requiring 49 precision machined cells in 7 sizes. The results of our manufacturing studies, which consider all of the manufacturing and tuning/test operations required to produce both types of equipment, indicate that the additional complexity associated with the CCL (e.g., 27 furnace brazes per segment) leads to a 15% higher overall cost for this structure, despite its lower design energy (1300 MeV for NCL vs 1780 MeV for SCL).

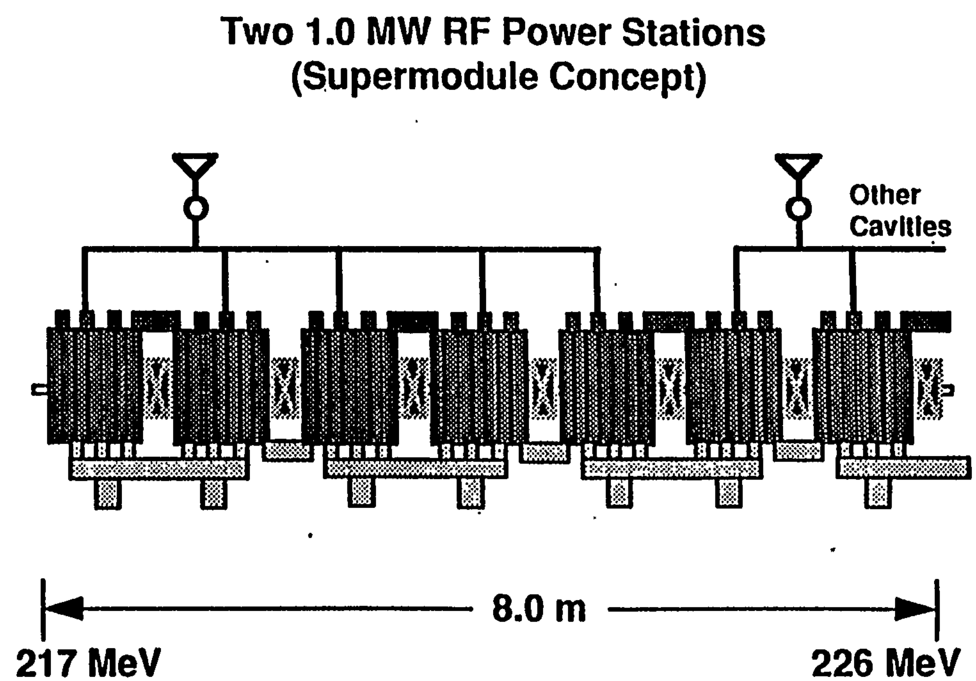
Relative Complexity Of NCL And SCL Structures

Med. β Cryomodule #1



SCL Cryomodule Details:
- 1 cryomodule assembly
- 15 identical cells (123 e-beam welds)
- 4 superconducting EMQs
- 6 50 l/s turbo pumps (in RF coupler)
- 3 cryogen loops

Comparable CCL Section



CCL Section Details:
- 7 flanged segments and bridge couplers
- 49 cells in 7 sizes (189 furnace brazes)
- 7 room temperature EMQs
- 7 500 l/s ion pumps
- 7 water loops (not shown in sketch)

Comparison Of Estimated Costs Of High Energy Linac Structures

The resulting cost estimates for the high energy linac sections of the superconducting and normal conducting linacs, above 217 MeV, are compared on the next page. As indicated earlier, the normal conducting machine costs more because there are more pieces and more time consuming precision machining and assembly operations per unit energy. This difference impacts not only the accelerating structure itself, but also supporting systems such as vacuum, beam diagnostics and instrumentation and control. This effect might be even more pronounced in the overall cost. However, because the higher accelerating field of the superconducting cavities is offset by their less efficient packing in the cryomodules, the overall length of the two linacs is similar and the cost advantage of the superconducting linac, although significant, is somewhat eroded.

Comparison Of Estimated Costs Of High Energy Linac Structures

(217 to 1300 MeV, $K-95)

Category	Superconducting	Normal Conducting
Total cost	$144,275	$170,088
Cost per MeV	$133	$157
Cost per meter	$145	$177
Number of accelerating cells installed	2010	4942
Cost per accelerating cell	$72	$34
Cells per segment	5	7
Cost per segment	$359	$241
Number of cryomodules installed	108	----
30 three segment module		
78 four segment modules		
Number of flanged sections	----	353
flanged section comprised of two segments		
Cost per cryomodule or flanged section	$1,336	$482

Combined effect of "More Pieces" outweighs the sizable cost of cryoplant required by superconducting linac

3.3.2.2 Capital Costs (~2 kg/yr Production)

As shown on the next page, the total capital cost of the superconducting linac, \$983 million before contingency, is \$104 million (10%) lower than the estimated capital cost of the normal conducting linac, \$1087 million. The low energy linac (to 217 MeV) is the same for both machines. With the exception of the thermal control subsystem, which is more expensive for the 2°K cryogenic superconducting linac, the cost of the high energy linac and associated services/subsystems for the normal conducting high energy linac are significantly higher than for the superconducting linac. Interestingly, despite the oversized RF power system for the SCL (able to produce 1780 MeV final energy for 3.15 kg/yr production), the RF power requirement for the less capable normal conducting system is still larger, corresponding to a 13% higher estimated cost.

The 10% advantage described above would be larger if the superconducting linac were sized for a directly comparable production level of 2.2 kg/yr. For example, the current baseline SCL uses only 560 kW of the available 840 kW per 1 MW RF power station in the high energy section. If the number of RF couplers per RF station were increased by 50% in the high energy section, then the number of RF stations could be decreased by 1/3 with a corresponding cost savings. This case is discussed in Section 4.

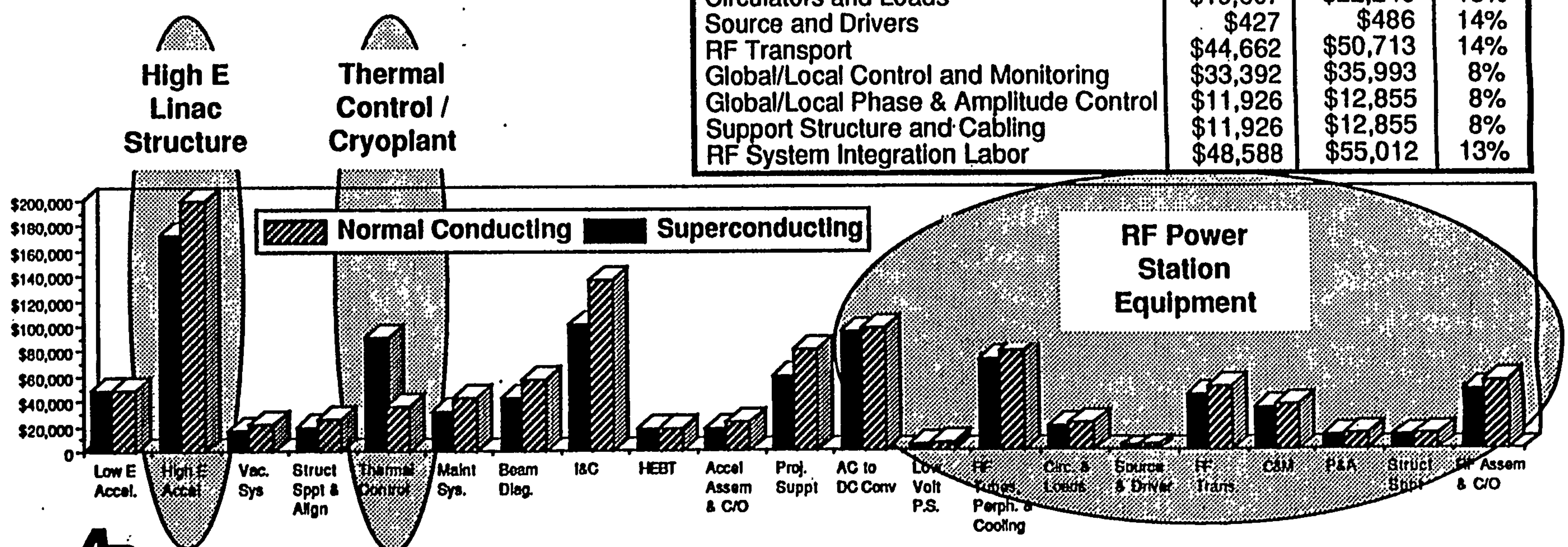
Superconducting & Normal Conducting Linac Capital Costs

(~ 2 kg/yr Production Level)

- *Total Cost Before Contingency*
- *Superconducting*: $982,949*
- *Normal Conducting:$1,086,665*
- *Delta: 11%*

* Superconducting machine capable of 3.15 kg/yr production by increase of coupler power from 140 kW to 210 kW

Capital Cost Categories	SCL	NCL	Δ%
Low Energy Linac	$49,755	$49,755	0%
High E Accel (100 MeV to Final Energy)	$173,972	$199,786	15%
Vacuum Systems	$16,791	$22,298	33%
Structural Support & Alignment	$19,563	$25,980	33%
Thermal Control	$92,663	$38,430	-59%
Maintenance Systems	$34,149	$45,192	32%
Beam Diagnostics	$43,004	$57,864	35%
Instrumentation & Control	$106,243	$144,174	36%
HEBT	$18,125	$18,125	0%
Linac Assembly and C/O	$19,734	$26,208	33%
Project Support	$64,608	$85,049	32%
AC to DC Conversion and Distribution	$95,232	$97,560	2%
Low Voltage Power Supplies	$5,573	$6,324	13%
RF Tubes, Peripherals, & Cooling	$73,010	$79,767	9%
Circulators and Loads	$19,607	$22,240	13%
Source and Drivers	$427	$486	14%
RF Transport	$44,662	$50,713	14%
Global/Local Control and Monitoring	$33,392	$35,993	8%
Global/Local Phase & Amplitude Control	$11,926	$12,855	8%
Support Structure and Cabling	$11,926	$12,855	8%
RF System Integration Labor	$48,588	$55,012	13%



Balance of Facility Capital Costs

A 1995 estimate of the costs for the balance of the APT facility was provided, for completeness, by Los Alamos, so that the total cost of the APT facility might be modeled. They are summarized on the next page. Although we expect a small difference in the balance of facility costs for the two alternatives as a function of the production rate, this difference has not been identified at this time and is not reflected in the numbers shown.

Balance of Facility Capital Costs

Acc.#	Category	Capital Cost	Contingency	P&FD Costs	Title 3	SE	Labor Count	Cost ($M-95)
21:	Structures & Improvements	$420.70	$98.85	$75.04	$21.04	$8.41	$26.12	$650.16
22:	Target/Blanket Facility	$221.35	$35.92	$49.95	$11.07	$4.43	$11.13	$333.84
23:	HEBT	$11.40	$2.42	$2.24	$0.57	$0.23	$0.49	$17.35
24:	Electrical Plant Equipment	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
25:	BOF & TEF	$231.78	$50.51	$40.10	$11.59	$4.64	$10.98	$349.60
26:	Heat Rejection	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
	Total:							$1,333.63*

** HEBT Cost Included In Accelerator Capital Cost Total*

Total "Overnight" Cost Comparison (~2 kg/yr Production)

The total overnight costs for APT plants based upon the superconducting and normal conducting linacs are summarized on the next page. [Again, recall that the SCL is capable of a higher production level.]

Total "Overnight" Cost Comparison: ~2 kg/yr Production

($M-95)

Superconducting*:	$2,526**
Normal Conducting:	$2,652**

* Capable of 3.15 kg/yr operation

** APT Plant Overnight Cost = Capital Cost x 1.2126 [Accel. Contingency] + Bal. Of Facility Cost

3.3.2.3 Capital Costs (~3 kg/yr Production)

This section provides capital cost estimates for an APT plant based upon an upgraded version of the normal conducting APT linac (as described in Section 3.2). As shown on the next page, the addition of new accelerating structures, the current funnel and additional RF power stations will increase the estimated capital cost of the linac by $143M, to $1,230M (or 13%). The results indicate that the cost increment for the upgraded capability is small compared with the investment required for the initial capability.

The capital cost of the superconducting linac for ~3 kg/yr production is the same as the capital cost for ~2 kg/yr production, which was provided in Section 3.3.2.2.

Capital Cost Impact Of Upgrading NCL To ~3 kg/yr Production

Cost Categories:	Cost
Second 20 MeV low energy accelerating leg	18.58
Funnel	12.00
Additional Vacuum/Thermal Control/I&C/etc.	18.16
Extra RF stations (66 ~1 MW)	90.37
Additional project support/coordination	3.80
	TOTAL:$143 M

Baseline Capital Costs (~3 kg/yr Production)

The estimated capital costs for the normal conducting and superconducting linacs, each sized for a tritium production of ~3 kg/yr, are compared on the next page. As indicated, the normal conducting linac is $247 million, or 25% more expensive in this comparison. Much of the additional cost can be attributed to the additional requirement for RF power, the additional complexity of the normal conducting high energy linac and the additional low energy leg of the linac (to 20 MeV).

Baseline Capital Costs: ~3 kg/yr Production

(~ 3 kg/yr Production Level)

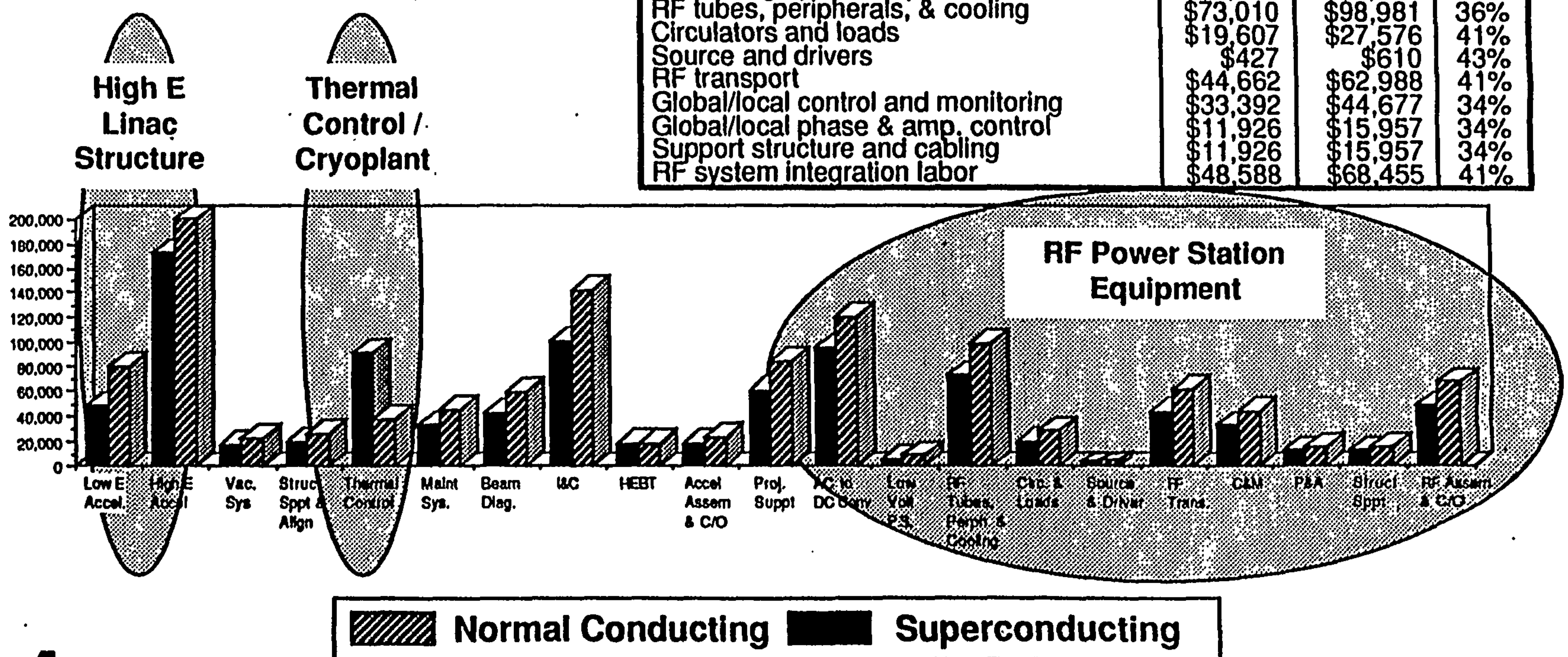
Total Cost Before Contingency

Superconducting: $983 M

Normal Conducting:$1,230 M

Delta: 25%

Capital Cost Categories	SCL	NCL	Δ%
Low energy linac	$49,755	$80,335	61%
High E Accel (100 MeV - final energy)	$173,972	$199,786	15%
Vacuum systems	$16,791	$23,825	42%
Structural support & alignment	$19,563	$27,394	40%
Thermal control	$92,663	$39,777	-57%
Maintenance systems	$34,149	$47,618	39%
Beam diagnostics	$43,004	$60,726	41%
Instrumentation & control	$106,243	$152,762	44%
HEBT	$18,125	$18,125	0%
Linac assembly and C/O	$19,734	$26,208	33%
Project support	$64,608	$88,849	38%
AC to DC conversion and distribution	$95,232	$121,138	27%
Low voltage power supplies	$5,573	$7,834	41%
RF tubes, peripherals, & cooling	$73,010	$98,981	36%
Circulators and loads	$19,607	$27,576	41%
Source and drivers	$427	$610	43%
RF transport	$44,662	$62,988	41%
Global/local control and monitoring	$33,392	$44,677	34%
Global/local phase & amp. control	$11,926	$15,957	34%
Support structure and cabling	$11,926	$15,957	34%
RF system integration labor	$48,588	$68,455	41%



Total "Overnight" Cost Comparison: ~3 kg/yr Production

The total overnight costs for APT plants based upon the superconducting and normal conducting linacs are summarized on the next page. These costs include linac contingency and the balance of facility costs as previously defined.

Total “Overnight” Cost Comparison): ~3 kg/yr Production

($M-95)

Superconducting:	$2,526
Normal Conducting:	$2,826

3.3.3 Annual Operating Costs

This section describes the annual operating costs of APT plants based upon normal conducting and superconducting linacs which produce sufficient beam energy and current in the target to generate ~2 and ~3 kg/yr of tritium. Section 3.3.3.1 describes the annual operating cost for ~2 kg/yr production while Section 3.3.3.2 addresses the costs for the higher production rate. All costs are referenced to 1995 dollars.

The reader should note that although the capital cost of the baseline superconducting linac does not change between the ~2 and ~3 kg/yr production levels, its operating cost is a function of the production level.

3.3.3.1 Annual Operating Costs (~2 kg/yr Production)

As shown on the next page, the total annual operation and maintenance cost of the APT plant with a superconducting linac, $192 $M/yr , is $23 $M/yr (11%) lower than the estimated annual operating cost with the normal conducting linac, 215 $M/yr. The major factor is reduced electricity consumption.

Operating and Maintenance Costs: ~2 kg/yr Production

($M/yr - 95)

Category	Superconducting		Normal Conducting	
Electric Charge	97.1		114.7	
Linac (including all subsystems)		82.02		99.53
Balance of Facility		15.12		15.12
Consumables	13.8		13.8	
Staffing	23.0		22.7	
Linac (including all subsystems)		13.30		12.99
Balance of Facility		9.69		9.69
Refurbishment/Replacement	58.3		63.8	
RF Tubes (main and driver)		15.28		17.60
RF HV DC Power Supplies		12.35		12.67
Injectors		0.24		0.24
LINAC Instrumentation & Diagnostics		4.98		6.62
Balance of System		25.46		26.64
TOTAL:	***192***		***215***	

Assumptions:
- *Cost of Electricity 1995 34.5 mils/kWeHr*
- *Average Salary 1995: $73,000*
- *Non-accelerator Staff: 200 FTE*

AC Power Requirement Comparison

The differences in the AC power requirements for APT plants based upon the the normal conducting and superconducting linacs are detailed on the next page. As shown, the major difference relates to the power required to drive the RF power system. This can be broken into two components: (1) resistive RF power losses in the normal conducting linac structures which have less of an impact on the superconducting linac, and (2) the lower electrical efficiency of the RF power stations in the superconducting design (which partly offsets its lower power requirement).

The table indicates a 16% lower power consumption for the superconducting system. This difference would be larger if the superconducting linac were sized for a maximum production level of ~2 kg/yr rather than ~3 kg/yr. Because the current baseline SCL uses only 560 kW of the available 840 kW per 1 MW RF power station in the high energy section, the individual stations operate well below the klystron saturation voltage and current, resulting in the indicated 3.5% loss of electrical efficiency. If the number of RF couplers per RF station were increased by 50% in the high energy section, then each station would be fully power loaded, with a restoration of the full electrical efficiency (same as normal conducting case). In this case, the power consumption for the superconducting linac would be reduced to 383 MWe, or 22% lower than the normal conducting linac.

AC Power Requirement Comparison

(MWe)

Category		Superconducting	Normal Conducting
Linac System		3	11
Injector, magnets, power supplies, diagnostics			
RF Power Systems		351	428
AC to RF conversion efficiency		41.2%	44.7%
Average main amplifier efficiency		54.8%	57.4%
Cryogenic Supply System		6	----
Balance of Facility		50	50
	TOTAL:	*410*	*489*

Assumptions:
1) ASM availability assessment determines days of operation for accelerator.
2) Facility AC requirement is assumed to be over entire year
3) Electric estimate from LA-CP-94-28, "APT Cost and Schedule Report - Preconceptual Design -", dated March 1994

Staffing Requirement Comparison

The estimated staffing requirement for the normal conducting and superconducting systems is compared on the following page. The required staffing is comparable. Future studies should address this area in more detail to better understand the requirements for maintenance and operation of each of the major linac subsystems and to identify potential areas for savings by early attention to maintainability in the design process.

Staffing Requirement Comparison

(Full Time Equivalents)

Category	Superconducting	Normal Conducting
Linac System	275	268
Overall Management	7.51	6.05
Operations Management	11.93	11.45
Maintenance Management	5.79	5.65
Technical/Engineering Support Management	18.52	17.51
Operations Crews	48.96	48.96
Technical/Engineering Support	25.27	25.27
Cryoplant Support	3.80	-------
RF Power Support	26.44	27.34
Instrumentation and Control Support	9.05	9.54
Beam Diagnostics Support	5.64	5.90
Linac Mechanical Design Support	11.27	11.91
Vacuum Support	4.43	4.63
Mechanical Structure	4.43	4.63
Indirect Support	91.53	89.43
Balance of Facility	200	200
TOTAL:	*475*	*468*

3.3.3.2 Annual Operating Costs (~3 kg/yr Production)

If the tritium production rate is increased from ~2 to ~3 kg/yr, then the O&M costs increase. These annual costs are shown on the next page. As indicated, the largest changes are attributable to the increased requirement for RF power (both cases) and the related costs (i.e., increased requirement to refurbish/replace RF power station equipment).

The results indicate that for ~3 kg/yr production, the superconducting system is estimated to have a 41 $M/yr (20%) lower annual operating cost. The improved relative advantage over ~2 kg/yr production is due to two factors. First, the ~3 kg/yr normal conducting linac requires new equipment (low energy linac, additional RF power, related equipment) which must be maintained while the superconducting linac remains the same. Second, at ~3 kg/yr production, all RF stations in the superconducting system are operating at full power and maximum electrical efficiency.

Annual Operating Costs: ~3 kg/yr Production

($M/yr - 95)

Category	Superconducting		Normal Conducting	
Electric Charge	111.47		133.21	
– Linac (including all subsystems)		96.21		118.09
– Balance of Facility		15.12		15.12
Consumables	13.83		13.83	
Staffing	22.99		23.17	
– Linac (including all subsystems)		13.30		13.48
– Balance of Facility		9.69		9.69
Refurbishment/Replacement	58.30		77.79	
– RF Tubes (main and driver)		15.28		27.51
– RF HV DC Power Supplies		12.35		19.81
– Injectors		0.24		0.60
– LINAC Instrumentation & Diagnostics		4.98		9.99
– Balance of System		25.46		19.88
TOTAL:	*207*		*248*	

Assumptions:
- *Cost of Electricity 1995: 345 mils/kWeHr*
- *Average Salary 21995: $73,000*
- *Non-accelerator Staff: 200 FTE*

3.3.4 Life Cycle Costs

This section describes the life cycle costs of APT plants based upon normal conducting and superconducting linacs that produce sufficient beam energy and current in the target to generate ~2 and ~3 kg/yr of tritium. Section 3.3.4.1 describes the life cycle costs for ~2 kg/yr production while Section 3.3.4.2 addresses the higher production rate.

The life cycle cost is intended to provide a single value which expresses the total cost of the APT facility and its operations over its 40 year lifetime. This quantity can be defined and normalized in several ways. For the purpose of this analysis, the life cycle cost is defined to be the overnight capital cost plus the sum of the operating costs where the operating costs for the second through 40th year are deflated by the factor $1/1.038^n$, where n is the year of operation. All costs are referenced to 1995 dollars. The above definition treats the out-year expenses in a manner similar to a net present value (NPV) analysis of the cash flow. For example, if the assumed escalation rate of the O&M expense is 3.8 %/yr and the assumed discount rate (value of government's money) is 7.7%/yr, then the net deflation factor for an NPV analysis would be (1.038/1.077) = 1/1.038.

Definition Of Life Cycle Cost

$$\text{Life Cycle Cost} \equiv \text{Total Overnight Cost} + \sum_{n=1}^{40} O\&M_n / (1.038)^n$$

(All costs referenced to 1995 dollars)

3.3.4.1 Life Cycle Costs: (~2 kg/yr Production)

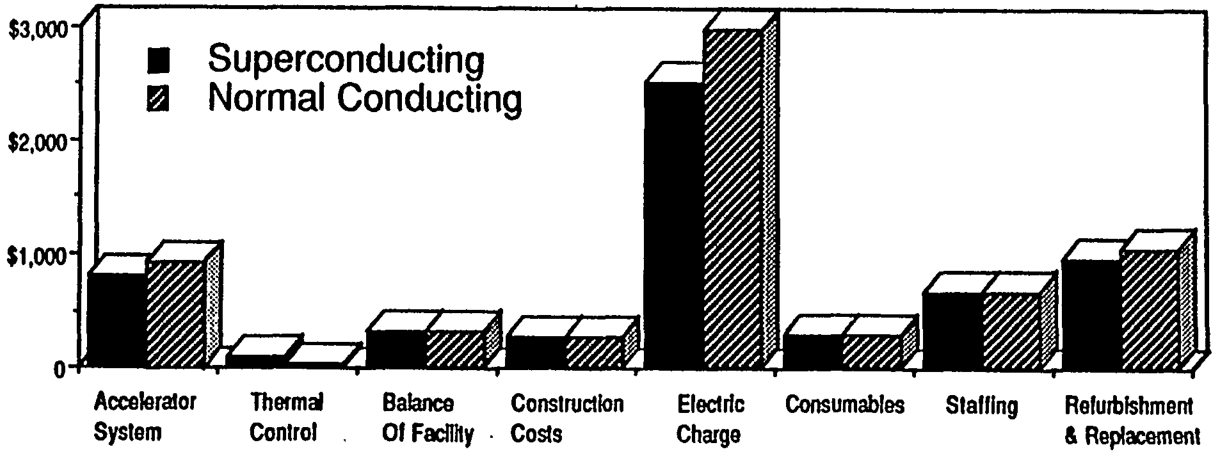
The life cycle costs for ~2 kg/yr production for the normal conducting and superconducting APT plants are indicated on the next page. As shown, the largest contributor to the life cycle cost is the capital cost of the APT plant (linac + thermal control + balance of facility), followed closely by the life cycle cost of electricity.

The life cycle cost of the superconducting APT system is $588million (9%) lower than that of the normal conducting APT system. The biggest contributors to this advantage are the linac system and the cost of electricity, which are 9% and 18% lower respectively for the superconducting alternative.

Life cycle Cost Comparison: ~2 kg/yr Production ($M-95)

Cost Categories:	Superconducting	Normal Conducting	Delta
Linac System*	1,192	1,317	125
Balance of Facility	1,334	1,334	------
Electric Charge	1,982	2,339	357
Consumables	282	282	------
Staffing	469	463	(6)
Refurbishment & Replacement	1,189	1,301	112
TOTAL:	*6,448*	*7,036*	*588*

• Incl. thermal control



Size Ordering of Differences

1 - Electric Charge: (++)
2 - Accel System: (+)
3 - Comp. R&R: (+)
4 - Thermal Control: (-)
5 - Staffing: (-)

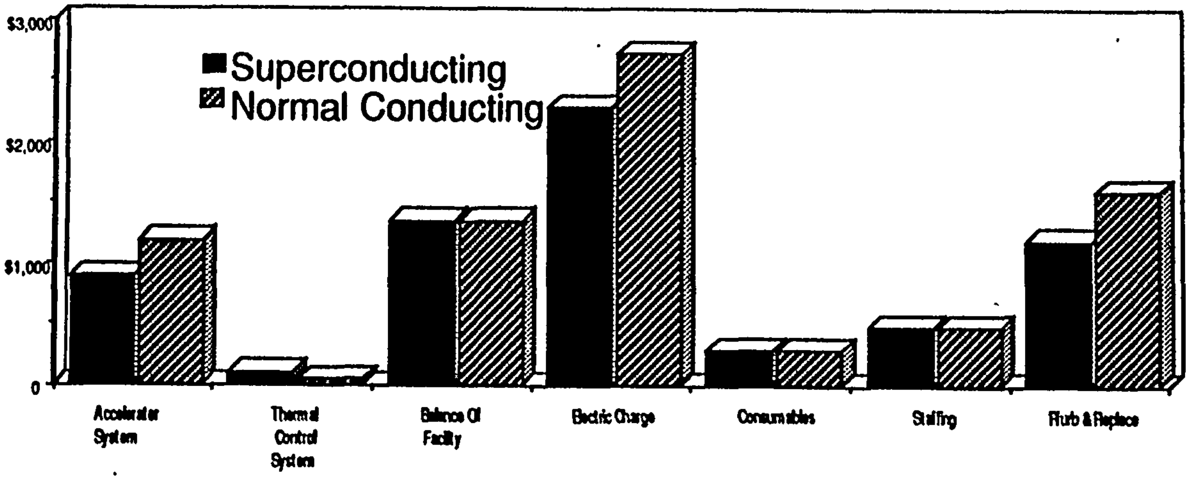
3.3.4.2 Life Cycle Costs (~3 kg/yr Production)

The life cycle costs for ~3 kg/yr production for the normal conducting and superconducting APT plants are indicated on the next page. As shown , the life cycle cost of the normal conducting APT system is $1.34 billion (20%) higher. Again, the biggest contributors to this difference are the linac system and the cost of electricity, which are 20% lower and 22% lower respectively for the superconducting alternative.

Life cycle Cost Comparison: ~3 kg/yr Production ($M-95)

Cost Categories:	Superconducting	Normal Conducting	Delta
Linac System*	1,192	1,492	300
Balance of Facility	1,334	1,334	------
Electric Charge	2,274	2,910	636
Consumables	282	282	------
Staffing	469	473	4
Refurbishment & Replacement	1,189	1,587	398
TOTAL:	*6,740*	*8,078*	*1,338*

• Incl. thermal control



Size Ordering of Differences

1 - Electric Charge: (++)
2 - Comp. R&R: (++)
3 - Accel System: (++)
4 - Thermal Control: (-)
5 - Staffing: (+)

3.3.5 Summary Of SCL Versus NCL Costs

The following chart summarizes and compares the estimated capital and operating costs, life cycle costs, and unit tritium production costs for APT plants based upon the normal and superconducting linac technologies at the lower (about 2 kg/yr) and higher (about 3 kg/yr) production levels. The capital, operating costs and life cycle costs are shown for the linac alone and for the entire APT plant (including the balance of facilities).

The unit tritium production costs are calculated according to two methods. The first method assumes that the plant availability in all cases will be a nominal 75%. This method decouples the economic assessment from the RAM assessment, which depends upon numerous independent assumptions (described in the next subsection). The second method factors in the results of the estimated plant availability based upon our RAM analysis.

Several observations are of interest. First, the NCL operating at the lower production level is estimated to have a higher capital, operating and life cycle cost than the SCL operating at the higher production level. This is reflected in the unit cost of tritium, which is over 50% higher for the NCL operating at the lower production level. If both machines are compared at the higher production level, the NCL has a unit cost that is over 30% higher. If both machines are compared at the lower production level, the NCL has a unit cost that is 13-18% higher.

Summary Of SCL Versus NCL Costs

	Lower Production Level			Higher Production Level		
• Linac Alone	SCL*	NCL	Δ (%)	SCL	NCL	Δ (%)
• Capital Cost ($M)	1192	1318	11	1192	1492	25
• Annual Operating Cost ($M/yr)	142	164	16	157	207	32
• Life Cycle Cost ($M)	4089	4664	14	4395	5715	30
• APT Plant						
• Capital Cost ($M)	2526	2652	5	2526	2826	12
• Annual Operating Cost ($M/yr)	192	215	12	207	257	24
• Life Cycle Cost ($M)	6443	7036	9	6749	8078	20
• Unit Tritium Production Costs						
• Beam Energy (MeV) / Current (mA)	1340/100	1300/100		1780/100	1300/136	
• Instantaneous Tritium Production Rate (kg/yr)	2.93	2.84		4.20	3.86	
• Tritium Production @75% Plant Availability (kg/yr)	2.20	2.13		3.15	2.90	
• Normalized Tritium Production Cost @75% Plant Availability	2.93	3.30	13	2.14	2.79	30
• Plant Avail. Predicted By RAM Model (%)	71.4	67.7**		71.4	67.7	
• Tritium Prod. @ Plant Avail. Predicted By RAM Model (kg/yr)	2.09	1.92**		3.00	2.61	
• Norm. Tritium Prod. Cost @Plant Avail. Predicted By RAM Model	3.08	3.66**	18**	2.25	3.10	38

* Superconducting machine capable of higher production level by increase of coupler power from 140 kW to 210 kW

** Plant availability assumed to be same as calculated for higher production level. This is conservative because configuration has no beam funnel and requires ~55 fewer rf power stations in the high energy linac. Therefore calculated unit costs will be in the high side.

3.4 Reliability/Availability/Maintainability/Inspectability (RAMI)

ASM RAMI estimates for the APT plant based upon the baseline normal and superconducting APT accelerators discussed in Section 3.1 are reported in this section.

The RAMI allocations for these two technology alternatives, for nominal tritium production levels of 2 and 3 kg/yr, respectively, are provided.

The objective of the RAMI analyses at the conceptual-design stage is to assist the designers in achieving an optimum design that balances the reliability and maintainability requirements among the subsystems and components. This balance is accomplished by developing the availability budget in two ways: top-down and bottom-up. The top-down process begins with the top-level requirement for the entire system and distributes it as allocations between subsystems, assemblies, and components. The bottom-up approach starts with availability estimates for the individual components and combines them to higher and higher levels. In practice, both budgets are combined into one, representing a balance between statistical estimates for the state-of-the-art items and the specification of requirements for the technology-development items. This is the approach followed in the analyses presented here.

3.4.1 Requirements Summary

The overall availability budget is dictated by the annual production required. Since this amount has not yet been clearly defined, for planning purposes, we shall use an annual planning quota of 3.0 kg. The SC APT system currently under consideration produces 0.479 grams of Tritium per hour. With this production rate, the total time required to produce 3.0 kg of tritium is 6257 hours, or 71% of the calendar year. The remaining 29 % of the time is divided between scheduled and corrective maintenance. A rational estimate of the amount of time required for scheduled maintenance requires development of a maintenance plan. It is a nontrivial endeavor and has not yet been performed. Reliability Centered Maintenance methods are recommended as the best methodology available at this time to develop such a plan.

Facility down-time will occur either as scheduled or unscheduled maintenance. For preliminary analysis purposes we use a scheduled maintenance allocation consisting of: four continuos weeks off (27 d x 24 h = 720 h) once a year and periodic maintenance periods alternating between 8 hours and 24 hours every two weeks (or an equivalent scheme), totaling 1008 hours and leaving 7752 h for scheduled operation. This plan is illustrated in the next slide. The scheduled maintenance defined in this way represents 12% of the calendar year. The remaining 17 % of the calendar year are thus available for corrective maintenance. The requirements are summarized in the next page.

Scheduled Maintenance Plan

12-month schedule:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	Maint.	Oper.	Total
JAN	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	o	o	o	o	648	96	744
FEB	o	o	o	SM	o	o	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	X	X	X	32	640	672
MAR	o	o	o	o	SM	o	o	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	32	712	744
APR	o	o	o	SM	o	o	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	X	32	688	720
MAY	o	o	SM	o	o	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	32	712	744
JUN	SM	o	o	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	X	40	680	720
JUL	o	o	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	o	o	32	712	744
AUG	o	o	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	o	o	o	o	32	712	744
SEP	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	o	o	o	o	o	X	32	688	720
OCT	o	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	o	o	o	o	o	o	32	712	744
NOV	o	o	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	o	o	o	o	o	o	X	32	688	720
DEC	o	o	o	o	o	o	o	LM	o	o	o	o	o	o	o	o	o	o	o	o	o	SM	o	o	o	o	o	o	o	o	o	32	712	744
																																1008	7752	8760

A = Annual Shutdown, SM = 8 hr maintenance, LM = 24 hr maintenance, O = Scheduled Operation

APT Accelerator Production of Tritium

Top Level RAMI Requirements

The scheduled maintenance defined above represents 12% of the calendar year. The remaining 17 % of the calendar year are thus available for corrective maintenance. Thus, the inherent availability requirement for the APT facility is 6257 h/7752 h = 0.8072. This number is distributed among the major parts of the system as shown: 0.85 for the accelerator, 0.9561 for the Target/ Blanket, and 0.973 for the Balance Of Plant. The Tritium Extraction Facility is assumed to contain enough redundancy to have no effect on the tritium production schedules. The availability requirements are summarized in the next page.

RAMI Requirements Summary

MACHINE CAPABILITY:

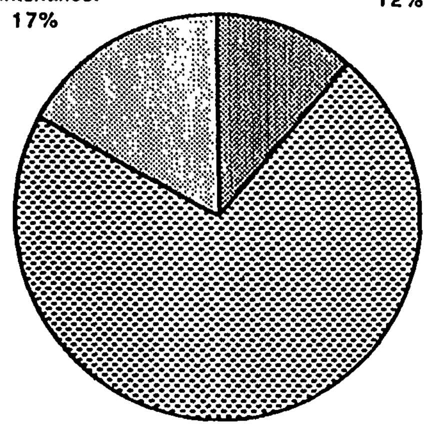
Beam Energy (MeV)	1780		
Beam Current (mA)	100		
Production Rate (kg/hr)	0:000479	4.20 (@100%)	3.15 (@75%)
Planned Annual Output Quota (kg)	3		

SCHEDULED MAINTENANCE	TOTAL HOURS	TOTAL DAYS	FRACTION
Scheduled Maintenance Total:	1008	42.0	0.1151
Scheduled Operation:	7752	323.0	0.8849
Required Production:	6257	260.7	0.7143
Corrective Maintenance:	1495	62.3	0.1706

INHERENT AVAILABILITY:

		REQUIREMENTS	ALLOCATION
SC Accelerator		0.8500	0.8502
Target/Blanket		0.9750	0.9750
Tritium Extraction		1.0000	1.0000
Balance Of Plant		0.9730	0.9730
Reserve	0%	1.0010	1.0000
Total APT Plant		0.8072	0.8066

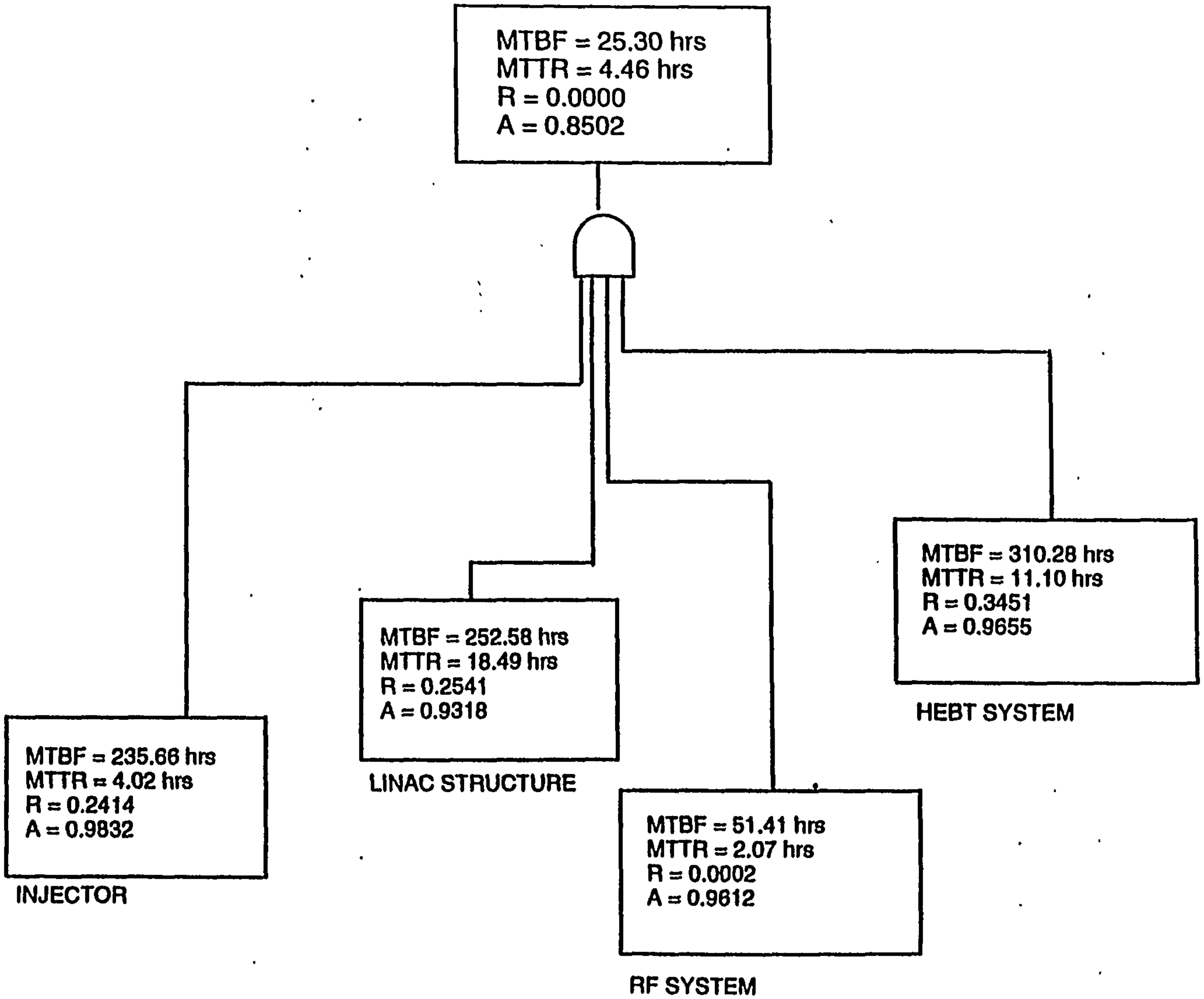
SC APT PRODUCTION AS ALLOCATED (kg): 3.00



3.4.2 SC APT System - RAMI Model

The APT accelerator system consists of four major subsystems: the injector, the linac, the RF system, and the HEBT. For the purpose of reliability and availability analyses, these four systems are assumed to be connected in series as shown in the next page, with the "AND" gate indicating a series connection. In RAMI, the series connection corresponds to the requirement that all subsystems have to be simultaneously fully functional for successful production of tritium. The probability of the simultaneous occurrence of reliable operation of all these components of the system is equal to the product of the probabilities of reliable operation of each one. Since availability and reliability are both measures of this probability, the top level system availability and reliability is obtained by multiplying the availabilities and reliabilities for individual systems. Furthermore, the series connection of individual subsystems corresponds to a case without redundancy. Should redundancy be present, the calculation of the top level availability, or reliability, must be performed using more complicated algorithms, as described in the section on Markov modeling. Graphically, the redundancies are indicated by means of an "OR" gate with a commentary indicating the type of redundancy, the number of spares, and the repair policy. As discussed in the following, each one of the four subsystems is in turn composed of subassemblies arranged in series or in various redundant topologies according to the individual design. The numbers listed in each box representing an individual system, or subsystem as the case may be, are the estimated values of that systems availability, A, reliability over a period of the mission, which is taken here to be 2 weeks - the shortest interval between two consecutive preventive maintenance periods, R, the Mean Time Between Failures, MTBF, in hours, and the Mean Time To Restore, MTTR, also in hours.

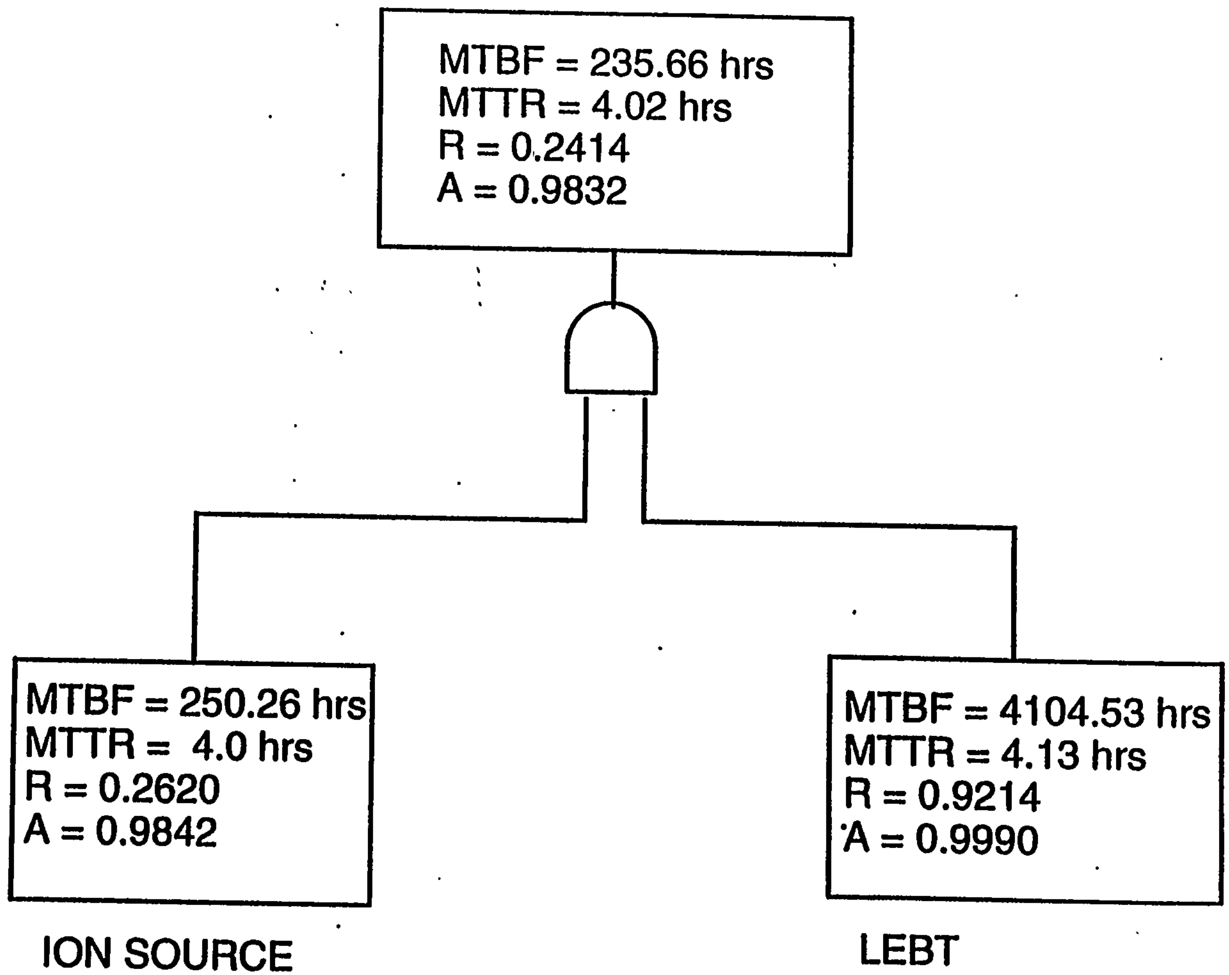
SC APT System - RAMI Model



3.4.2.1 Injector - RAMI Model

The APT Injector consists of two main components: the Ion Source and the LEBT. These two items are assumed to be connected in series as shown in the next page.

Injector - RAMI Model



ECR Ion Source - RAMI Model

The ion source, in turn, consists of the microwave window, microwave power supply, extractor assembly, gas supply, accelerating column, magnet polypropylene insulator, HV power supply, vacuum system, and the support structure. Several candidate ion source concepts are under consideration. The Electron Cyclotron Resonance (ECR) ion source concept, favored by the designers for its promising reliability, is the one represented. The RAMI topology of the ion source is shown in here. All MTTR values in the ion source are assumed to be 4 hrs, reflecting a crucial assumption adopted in the design that in the event of an injector failure, a spare injector assembly shall be wheeled into the tunnel after removal of the failed one. This procedure shall be quite routine, being used during the biweekly injector replacements, and is therefore expected to be quick. The biweekly injector replacements are dictated by the current state of the art in the ion source technology where long life of sensitive components, such as the microwave window, had not yet been demonstrated.

The microwave window with an MTBF of 300 h is the most significant contributor to the ion source's, and as a consequence, the injector's availability. With this MTBF value, the expected number of unscheduled microwave window replacements required on the average over one year's period is ~26 and the total time spent in repairing the source is ~52 h. The expected number of scheduled replacements of the microwave window is dictated by the lifetime of the window. The ECR ion source shows promise of lifetimes on the order of 300-1000 hours based on extrapolation of experimental data available to date. The present maintenance plan takes this into account by scheduling an ion source replacement once every 336 hours (two weeks) of operation but the preventive replacement does not eliminate the possibility of a random failure.

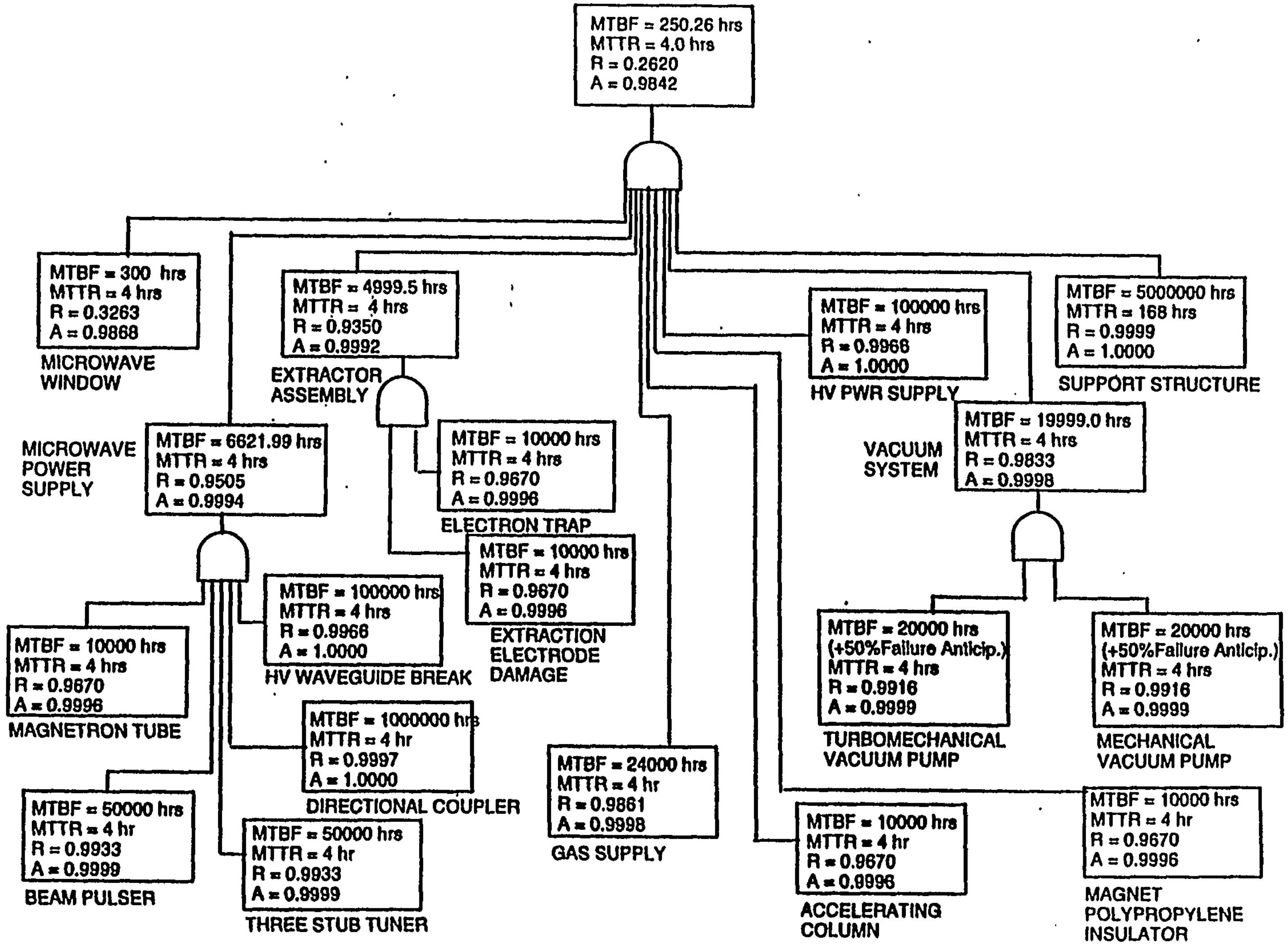
ECR Ion Source - RAMI Model

One should keep in mind here a clear distinction between the life of the source, which would be deterministic, and MTBF which is the inverse of the random failure rate, is determined by the random rate of various voltage surges and spikes stressing the source beyond its capabilities. The failure mechanisms involved are not completely characterized for any one of the proposed sources and the estimates of the MTBF for the random source failures are uncertain. Ideally, the MTBF of the source should be such that the reliability of its operation for the 336 hours between scheduled replacements is at least 90%. The MTBF corresponding to 90% reliability for two weeks is 3189 hours. To demonstrate such an MTBF with 95% confidence, the window would be required to operate for 9535 hours (factor 2.99) to first failure (reference: "Reliability Handbook" by W. Grant Ireson, ed., McGraw-Hill, 1966).

In the RAMI budget analysis presented here, a more conservative MTBF of 300 hours are allowed. The number is consistent with engineering evaluation of technology currently available or achievable with minimum development. Any improvement achieved by lengthening the MTBF will also satisfy the overall system requirement.

With the 300 hour MTBF assumed above, the reliability of the microwave window is only ~33 %. This means that in an average year, only for 9 out of the 26 biweekly periods between scheduled maintenance, will the microwave window live through the entire period from one scheduled replacement to the other. Most of the time, it will fail unexpectedly in between and force a corrective maintenance and a beam outage for about 4 hours. Over time, this could be a real nuisance. One can reasonably expect, however, that this issue will eventually be resolved and reliability of the ion sources will come under control. A design alternative, consisting of two sources in a redundant configuration was briefly evaluated in this conceptual design phase. The use of a redundant source would raise the reliability of the injector system to 99%. In this concept, the beam was directed into the same LEBT from either one of the two sources by means of a dipole magnet with reversible polarity

ECR Ion Source - RAMI Model



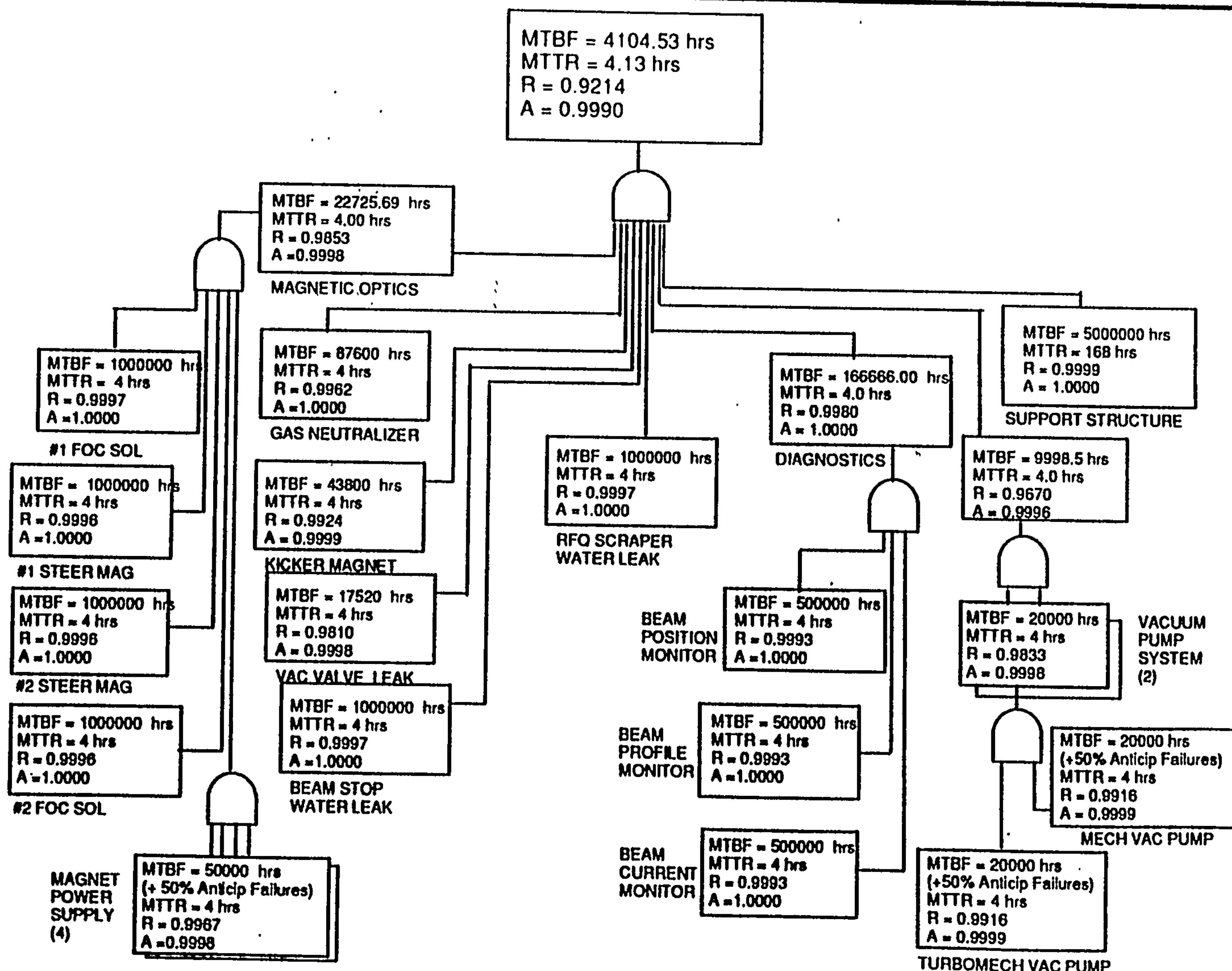
LEBT - RAMI Model

The LEBT consists of magnetic optics, gas neutralizer, kicker magnet, vacuum valves, beam stop, RFQ scraper, diagnostics, vacuum system, and the support structure as shown.

The LEBT, like the ion source, is assumed to be mounted on the same wheeled cart which would be rolled into the accelerator tunnel in case of an unscheduled or scheduled repair. The proposed arrangement is expected to reduce the average repair time down to about 4 hours as indicated by the MTTR values on the diagram.

It is important to note that the MTBF for the beam stop water (coolant) leak and the RFQ scraper water leak are predicated on the assumption of regular replacements of these items which are expected to exhibit significant wearout. The planned preventive replacement frequency is 6 months at this time.

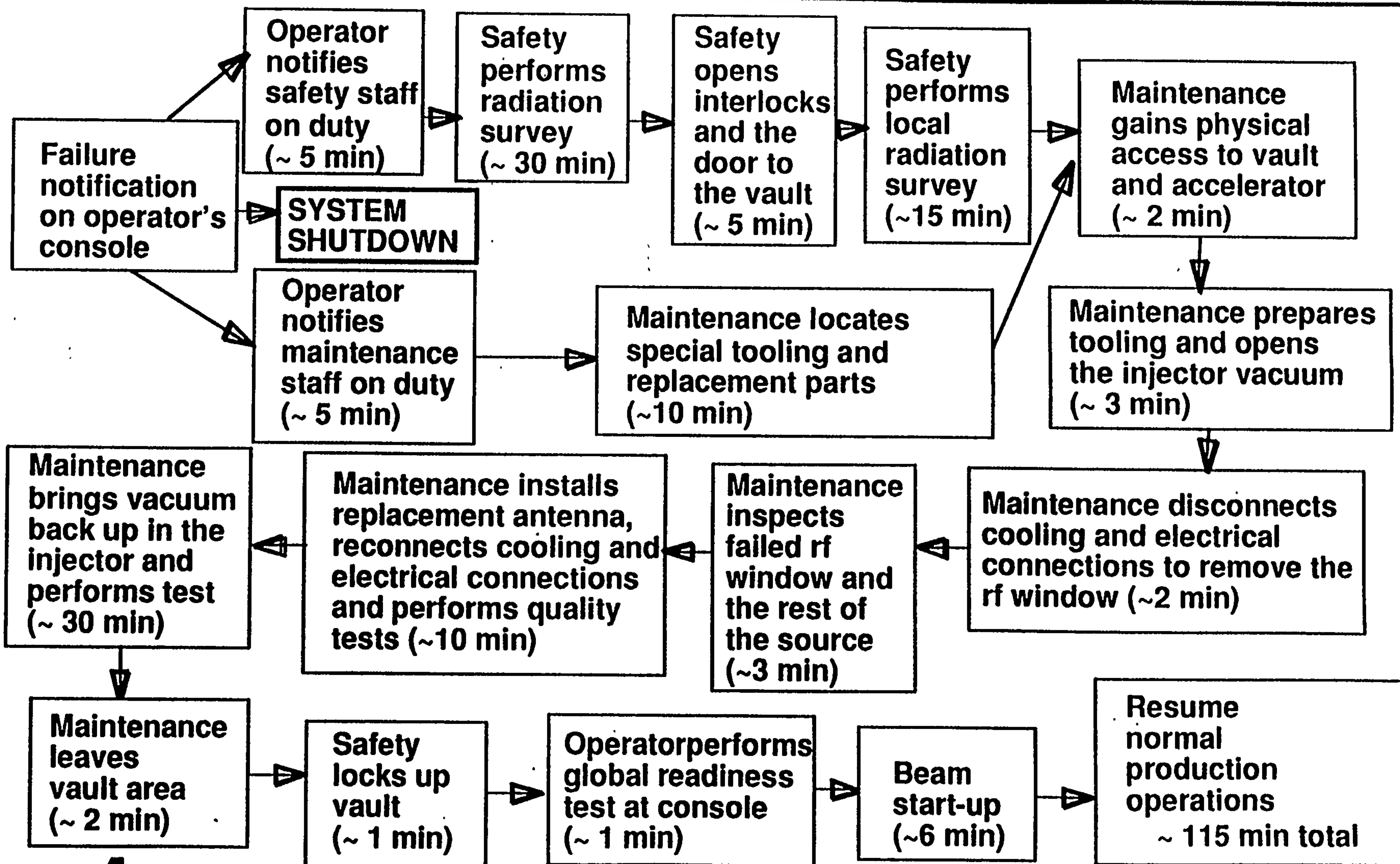
LEBT - RAMI Model



Ion Source Window Replacement

The current baseline design assumes that a spare injector assembly shall be wheeled into the tunnel after removal of the failed one. This procedure shall be quite routine, being used during the biweekly injector replacements, and is therefore expected to be quick. Other alternatives, consisting of improved maintainability of the individual components by use of modular subassemblies, quick disconnects, etc. are also under consideration. This diagram illustrates a timeline analysis for ion source RF window replacement with a potential quick maintainability design.

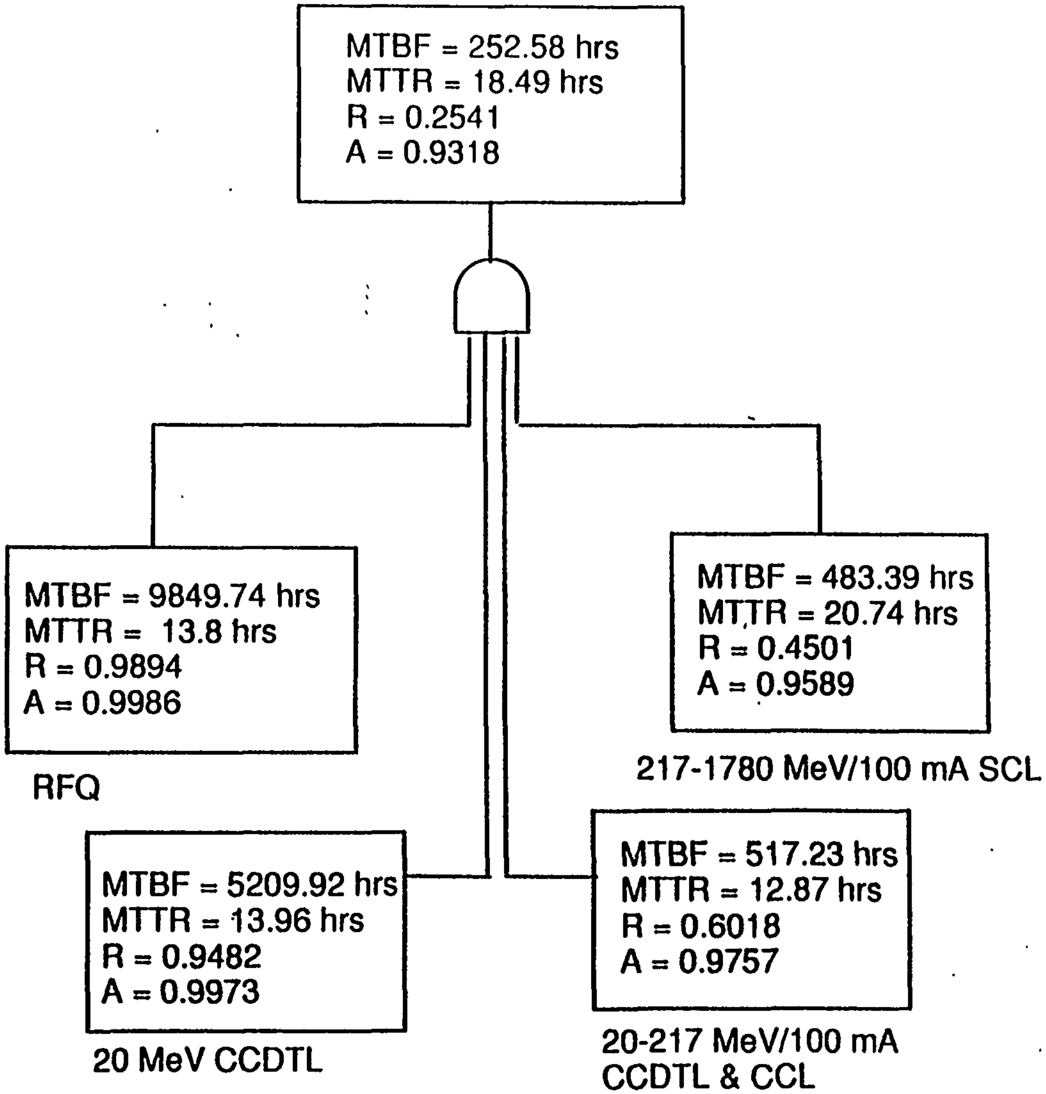
Ion Source Window Replacement



3.4.2.2 SC LINAC - RAMI Model

The APT linac consists of three major components: the Radio Frequency Quadrupole (RFQ), the Coupled Cavity Drift Tube Linac (CCDTL), the Coupled Cavity Linac (CCL), and the Super Conducting Linac (SCL). The CCDTL and the CCL are termed the Front End CCDTL & CCL here. The RFQ and the Front End CCDTL & CCL are identical to the corresponding part of the Room Temperature Linac (RT Linac) which has also been modeled but is not discussed in this presentation. All three components of the SC Linac are assumed to be in series in the RAMI model as indicated with the "AND" gate.

SC LINAC - RAMI Model

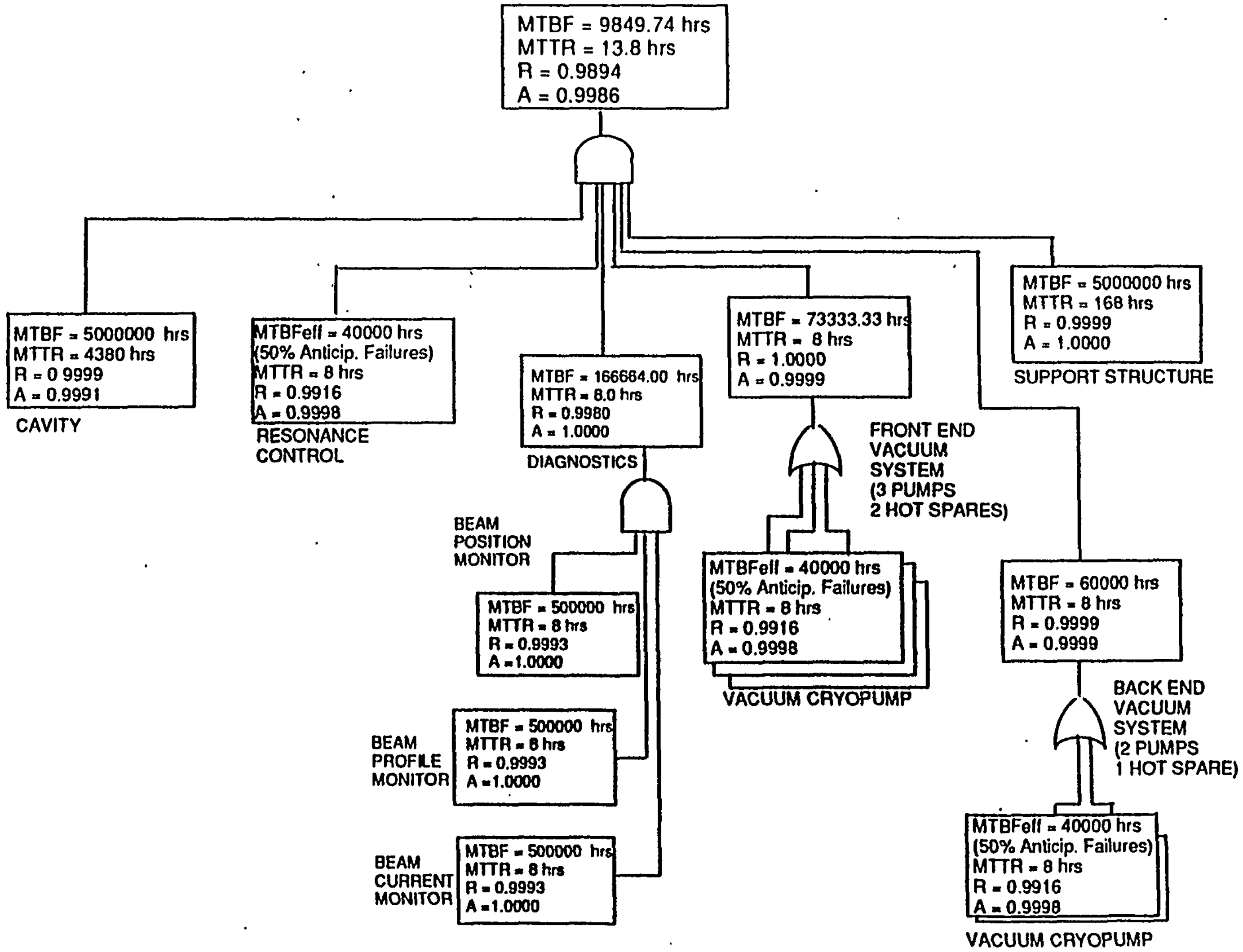


RFQ Supermodule - RAMI Model

The individual subsystems of the SC Linac have been modeled to a deeper level, as shown here for the RFQ. The RAMI model of the RFQ consists of the RFQ cavity, a resonant control system, diagnostics, vacuum system, and the support structure. The RFQ RF power system is handled separately under the heading of RF system. The "OR" gates in the resonance control system, diagnostic system, and vacuum system indicate the corresponding redundancies as noted by the attached comments. The vacuum system has been represented as two parts in series, the front end with 3 pumps and the back end with two pumps. The front end vacuum system is capable to tolerate two pump failures and the back end is able to tolerate one pump failure. This assumption holds when the failure occurs during steady state operation, i.e. when the initial gas load has been pumped away and the subsequent gas loads are small.

The resonance control system, responsible for control of the resonant frequency of the accelerating cavity via control of its temperature, and the diagnostics have not yet been designed at the time of this modeling analysis to the level required for reliability modeling where the individual components are identified.

RFQ Supermodule - RAMI Model



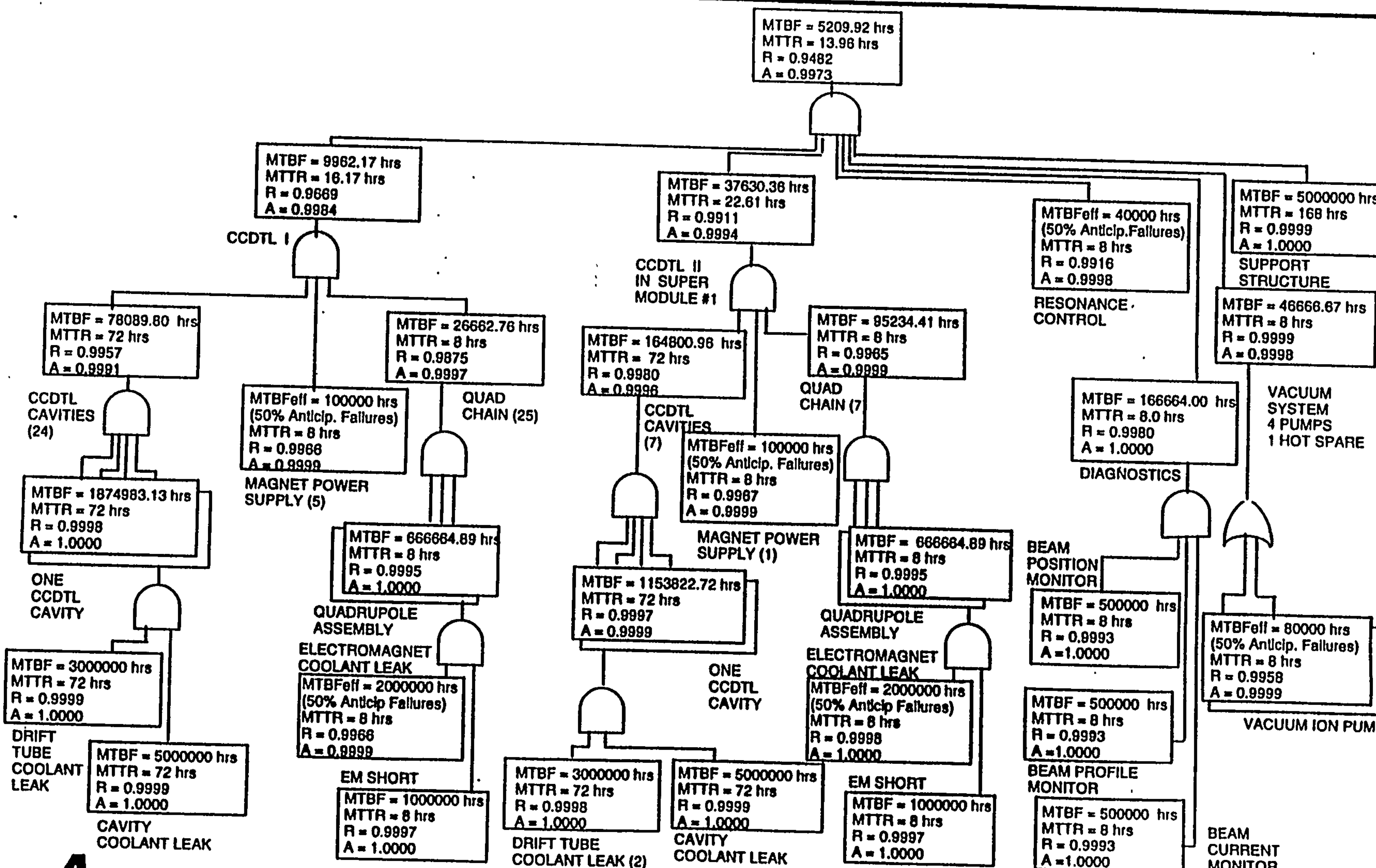
7-20 MeV Linac RAMI Model

The next page shows the RAMI model of the first supermodule. The RAMI models for the other supermodules are similar in general arrangement, but differ in the actual accelerating structures used and the numbers of elements. Each supermodule consists of a segment of an accelerating structure and the associated supporting equipment. Some supermodules span across several accelerating structure type, especially in the low energy region, where several types of CCDTL and CCL are employed over a relatively short distance. For example, supermodule number 1, shown in the figure consists in part of the CCDTL I (single drift tube CCDTL) and in part of the CCDTL II (two drift tube CCDTL). The model represents the reliability of the accelerating structures in proportion to their parts count, i.e. the number of accelerating cells. The most significant failure mode which is of concern for these elements is the coolant (water) leak. A leak could potentially occur either in the cavity wall, or in the drift tube itself, along the various braze tracks. Although the probability of any such leak for an individual cell is vanishingly small, it could be important in view of the quantity of cells used in the design. Hence, it is included in the model.

Another element of the accelerating structure included in the RAMI model is the quadrupole lens. The failure rate used for each quadrupole lens in the RAMI model is consistent with the numbers quoted in the LANSCE RAMI Upgrade Study, representing the best historical database for this type of machine available at this time.

The other components of the supermodule are the resonance control system, the diagnostics, the vacuum system, and the support structure. The RF system is modeled separately. The number of vacuum pumps has not been defined for each individual supermodule at the time of this analysis. Hence, an approximate number, proportional to the length of the accelerating structure in question has been assumed for this preliminary analysis. It will require modification once the details become available. For the supermodule number 1, 4 ion vacuum pumps have been assumed with a capability for fully functional operation with one pump failed. This assumption is deemed reasonable once the initial air has been evacuated from the system and the vacuum has been stabilized. No on-line repairs are assumed possible for the vacuum system, the resonance control system, or the diagnostics system, since most repairs for these items will likely require the workmen to enter the accelerator tunnel and operate in close vicinity of the accelerator.

7-20 MeV (Supermodule #1) CCDTL Linac RAMI Model

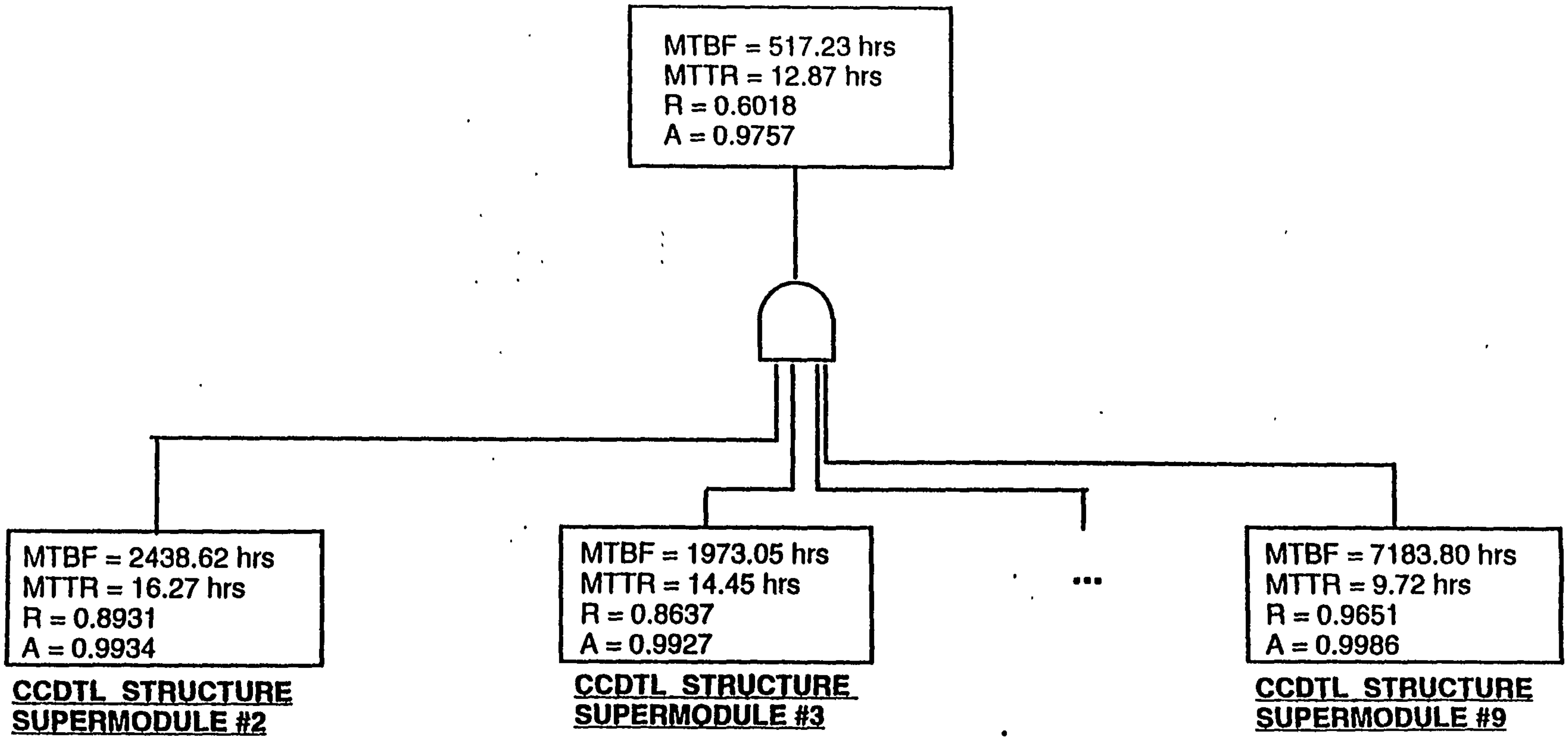


Accelerator Production of Tritium

20-217 MeV CCDTL/CCL LINAC - RAMI Model

The 20-217 MeV CCDTL & CCL consist of the remaining 8 supermodules as shown on the next page. The RAMI model for each supermodule resembles the one shown previously. All supermodules are required for beam production. Hence, they are connected in series in the RAMI diagram.

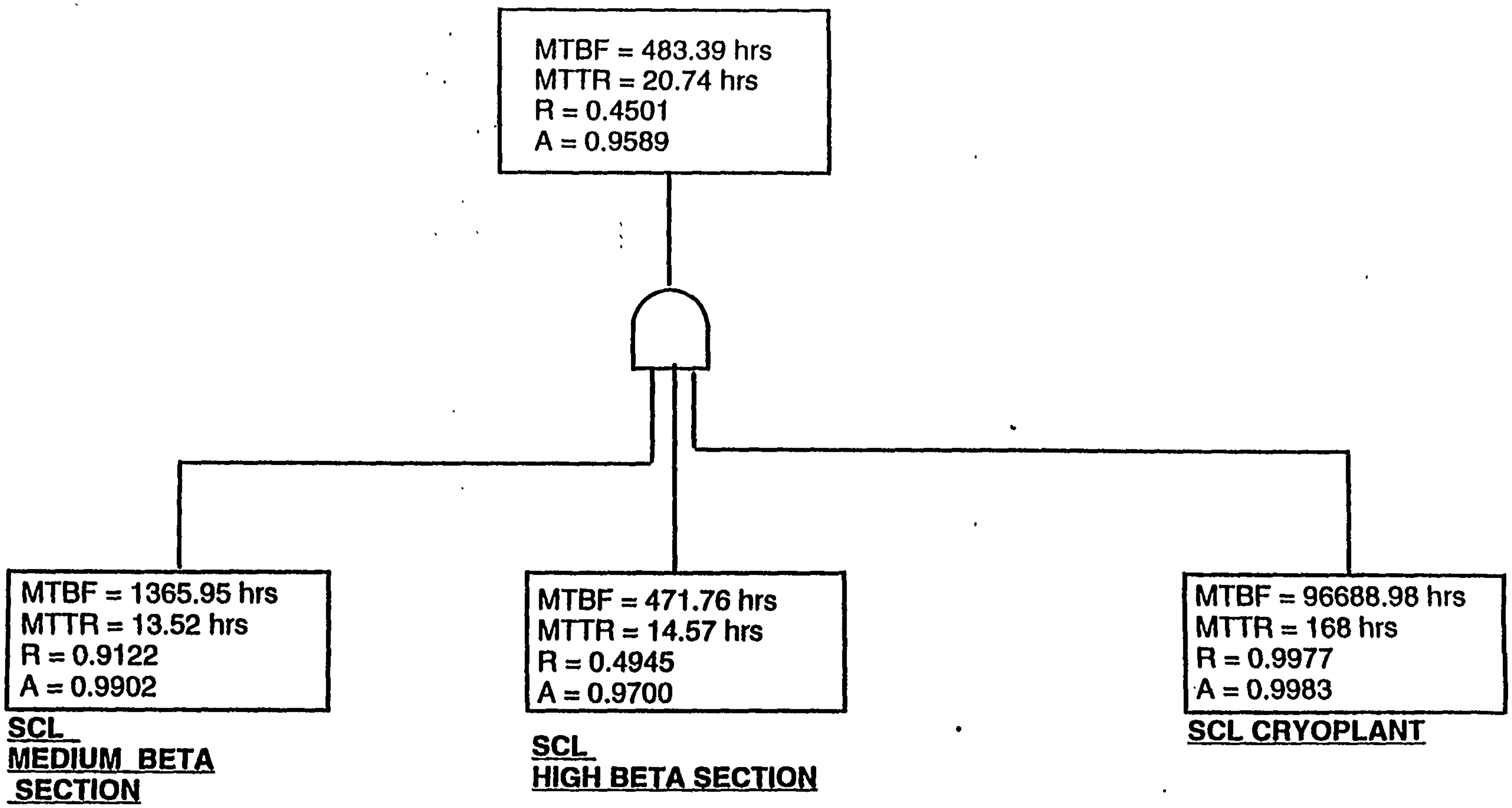
20-217 MeV CCDTL/CCL LINAC - RAMI Model



SCL - RAMI Model

The remainder of the SC Linac is the SCL (this terminology leaves a lot to be desired but it is used here in the sense that SC Linac includes both the room temperature and the superconducting portions of the superconducting version of the APT accelerator) which consists of the SCL section 1 (medium beta section) and SCL section 2 (high beta section), and the SCL cryoplant supplying the liquid helium. The RAMI model assumes a series connection for these subsystems as shown in the next page.

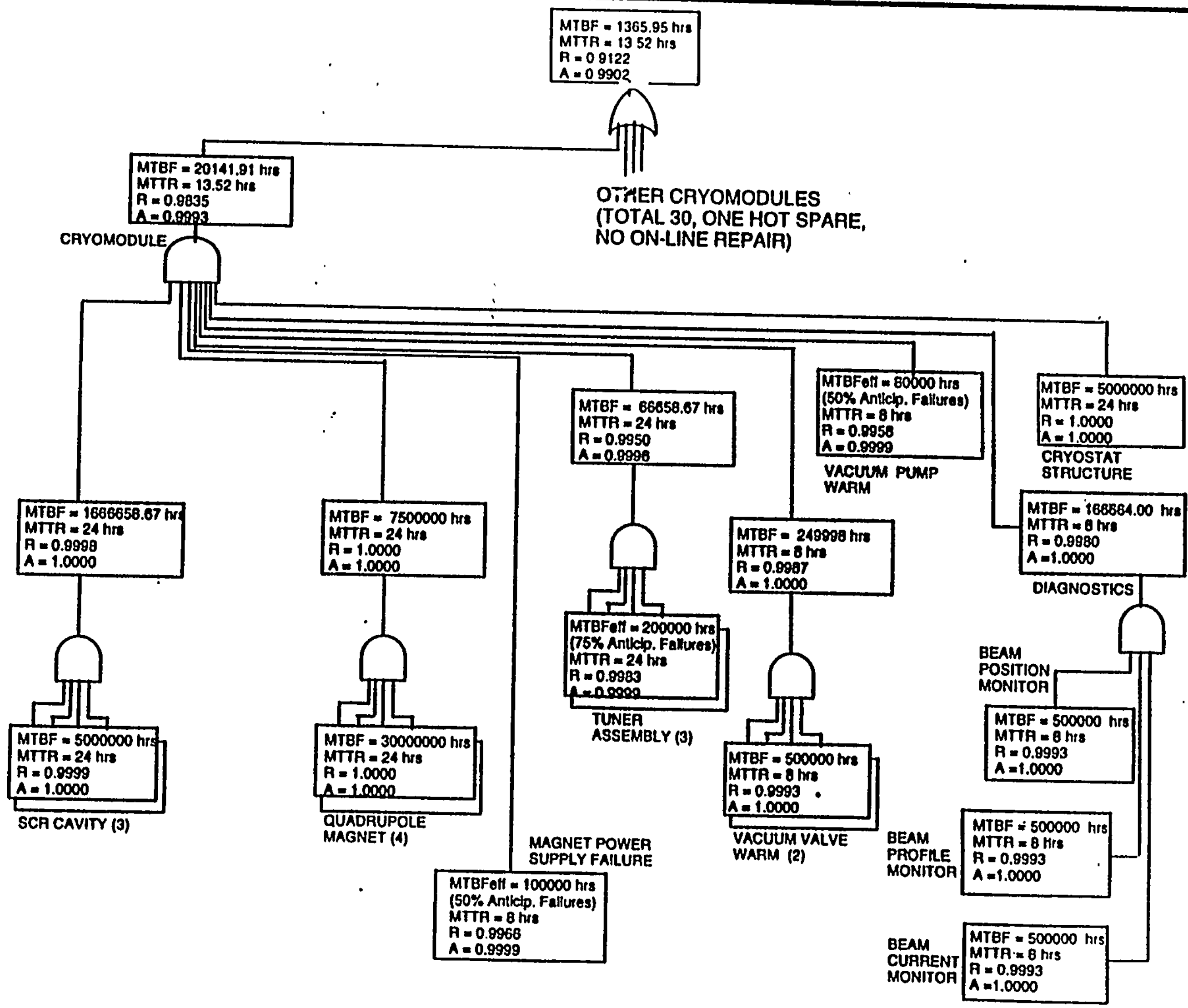
217-1780 MeV SCL - RAMI Model



SCL Section 1 (Medium Beta) - RAMI Model

SCL medium beta section consists of 30 identical cryomodules. The RAMI analysis assumes that this chain of cryomodules can tolerate one failure. The repairs, however are not possible on-line since any work on the cryomodules requires access to the accelerator tunnel. Accordingly, the system has been modeled as a system with one hot redundancy with off line repair policy. The modeling approach will require refinement in the next stage of the RAMI analysis to allow for partial failures of the modules and the associated capability to operate through various degraded failure modes. The MTTR of 24 hours used for each cryomodule is based on the assumption that a replacement cryomodule will be ready in a fully conditioned and cold state at all times and that a fully trained maintenance crew will also be present on site at all times.This number is consistent with the reported CEBAF (Thomas Jefferson National Laboratory) operational experience.

SCL Section 1 (Medium Beta) - RAMI Model



Modeling the Failure Tolerability of the SC Linac

It is expected that the beam dynamics considerations would likely not tolerate four contiguous cryomodule failures. Therefore, we are allowing one tolerable failure per segment of around 20 modules each in the High Beta SCL section. Such assumption still permits inclusion of states with two cryomodules failed adjacent to each other within two neighboring segments and is therefore slightly nonconservative if in reality such states are not tolerable by the beam dynamics.

Modeling the Failure Tolerability of the SC Linac

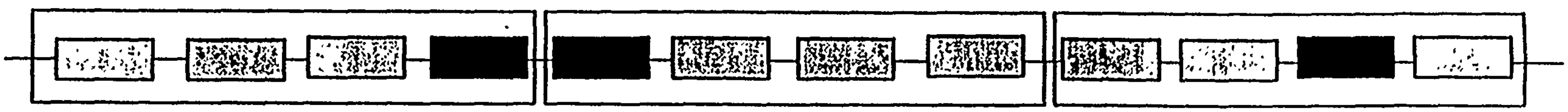
- Not All Failed States Are Tolerable - The Ones w/Adjacent Failures Are Not:

- Beam Dynamics Prefers A TBD Distance Between Failed Cryomodules:

- Standard Reliability Equations Disregard The Ordering Of The Equipments
  - States with adjacent failed cryomodules are allowed
  - Availability is overestimated (non-conservative)

- The Exact Solution has been derived for the case of Two Failed Cryomodules in the linac chain
  - It shows that the dependence of availability on separation is weak
  - The case of three or more failed cryomodules will be examined

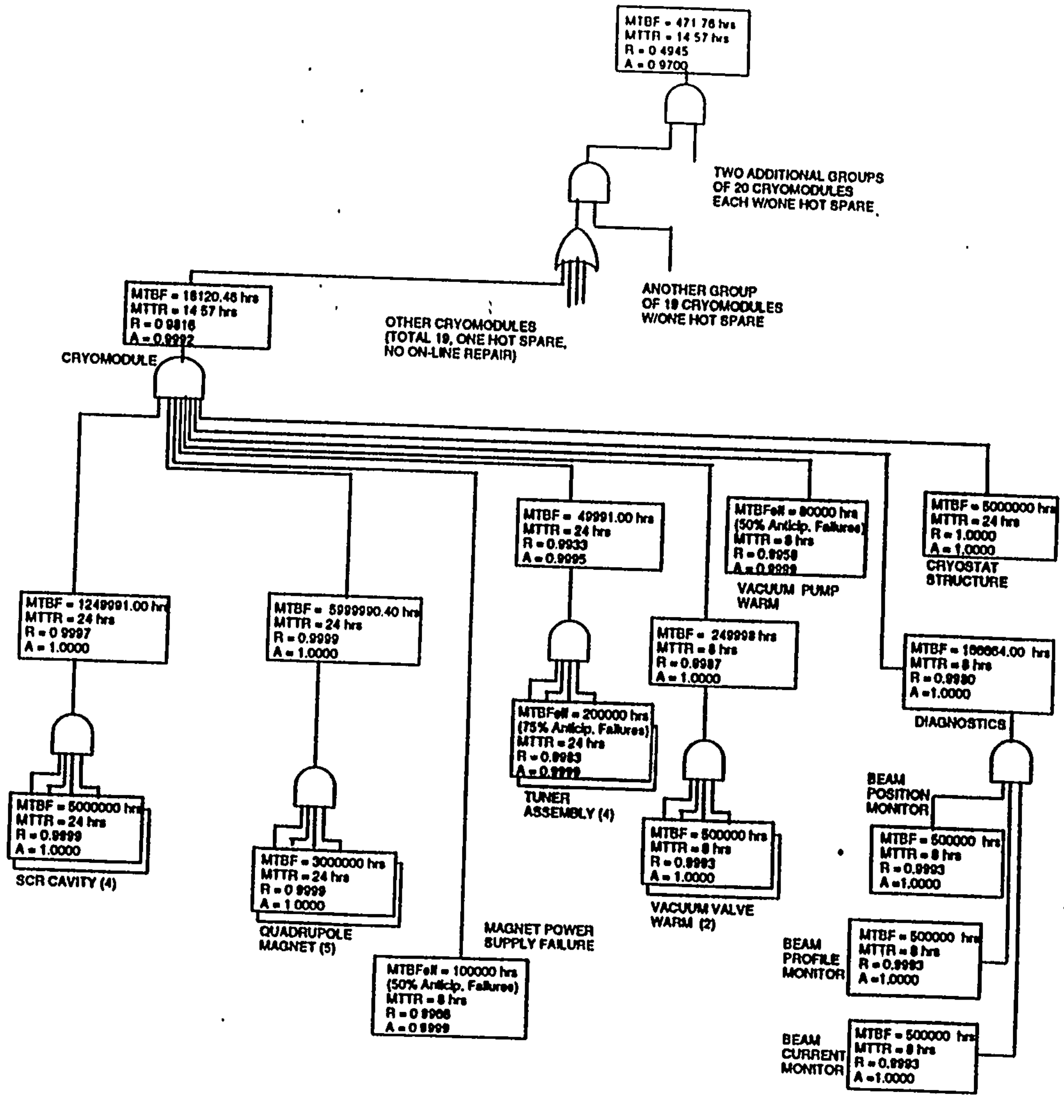
- An approximate solution: split the linac into segments, with one failure tolerable in each
  - Works well for relatively small number of failures tolerable
  - Adjacent failures still allowed at the ends of the segments



SCL Section 2 (High Beta) - RAMI Model

The RAMI model of the SCL high beta section is similar to the one for the medium beta section, except that the 78 cryomodules in the high beta section are divided into four groups of approximately 20 cryomodules each to satisfy the condition of separation of the spares. This section of the SCL is thus assumed to be capable to operate through four cryomodule failures.

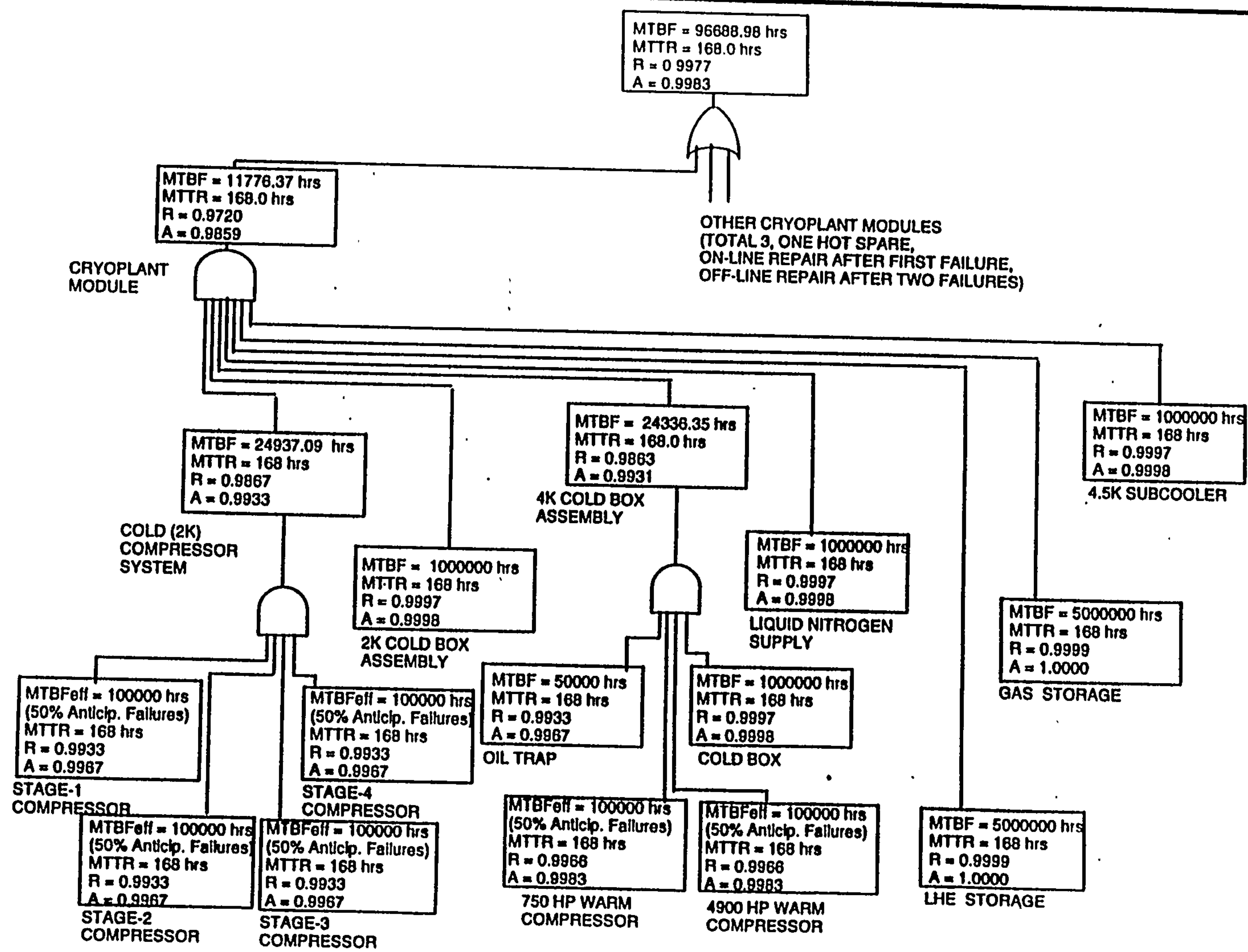
SCL Section 2 (High Beta) - RAMI Model



SCL Cryoplant - RAMI Model

The cryoplant, supplying the SCL with liquid He at 2 K is included under the SCL budget. Its RAMI model is shown in the next page. The cryoplant consists of three cryoplant modules with capacity for providing close to full operational cryogen supply with only two cryoplant modules in operation. Each cryoplant module includes the cold compressor system, 2 K cold box assembly, 4 K cold box assembly, liquid nitrogen supply, liquid He storage, gaseous He storage, and the 4.5 K subcooler. The cryoplant is represented as a redundant arrangement of cryoplant modules, modeled by means of the 4-state Markov model where on line repairs are possible with a single module failure but off line repairs are necessary when a second module fails. Since Helium storage for one week's operation exists in the cryoplant, the impact of a short failure of one of the cryoplant modules will be minimal. The exact modeling of the various possible states of this system requires a refinement of the model to account for possible degraded operation modes which will be done in the next phase of the effort.

SCL Cryoplant - RAMI Model

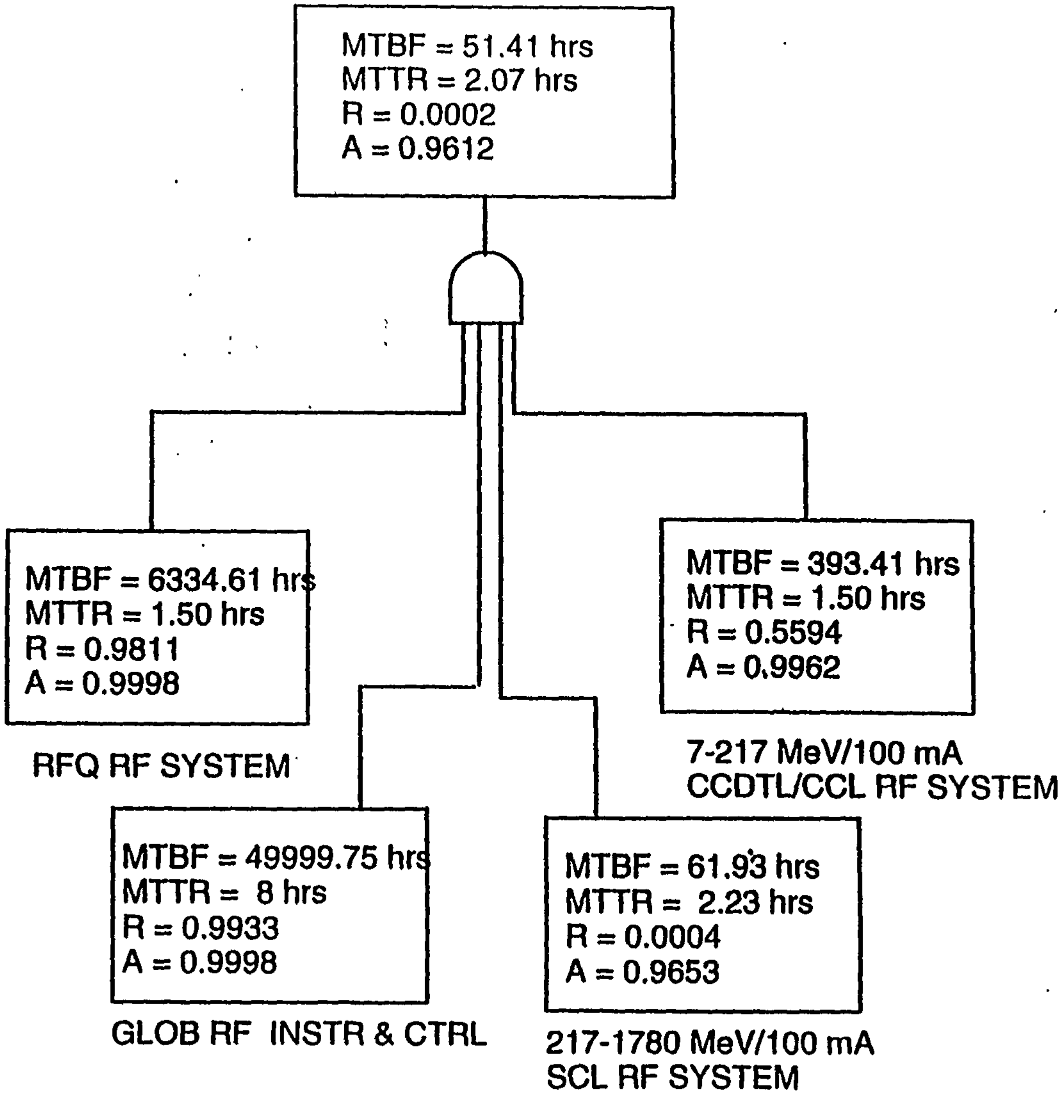


Accelerator Production of Tritium

3.4.2.3 SC APT Accelerator RF System - RAMI Model

The RAMI model of the SC Linac RF system is shown in the next page. It consists of the RFQ RF system, Front End CCDTL/CCL RF system, SCL RF system, and global RF controls (which include the master oscillator and the phase reference distribution system).

SC APT Accelerator RF System - RAMI Model



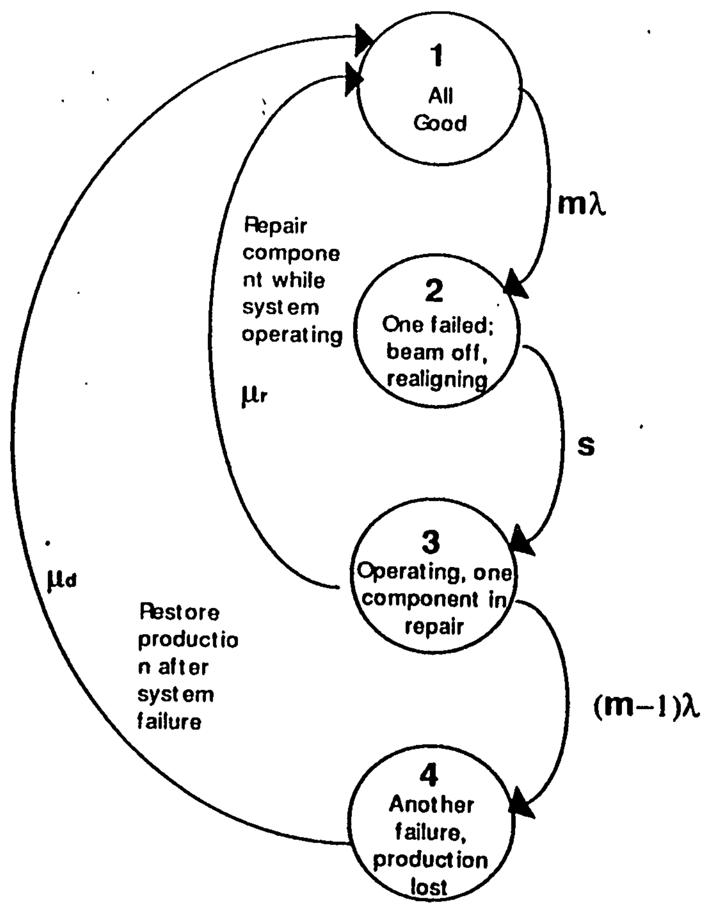
The 4-State Markov Model

The 4-state Markov model shown in the next page is used to represent the RAMI characteristics of the systems with on-line repair like the RF supermodules. This model assumes that the system remains on, after only a brief interval necessary to isolate the failed unit, when one module, i.e. an RF station, fails. The assumption is that the system is capable of handling the load for a short time without complete offloading of the grid. However, when the second module fails, the system must be brought down and repairs are then performed on both failed modules until both are complete. Then, the system is turned back on. This time, however, an extra time for ramping the grid load is required. Similar repair policies are followed for failures in the SC linac cryomodules.

Other repair policies are possible. For example, one could bring the system back up as soon as at least one of the failed modules is repaired. Presumably, this policy would result in better availability. Further investigation of the various alternatives and their practicability is necessary before a final recommendation is made.

The 4-State Markov Model

System:
Total of m components;
System operable after realignment with m-1



Accelerator Production of Tritium

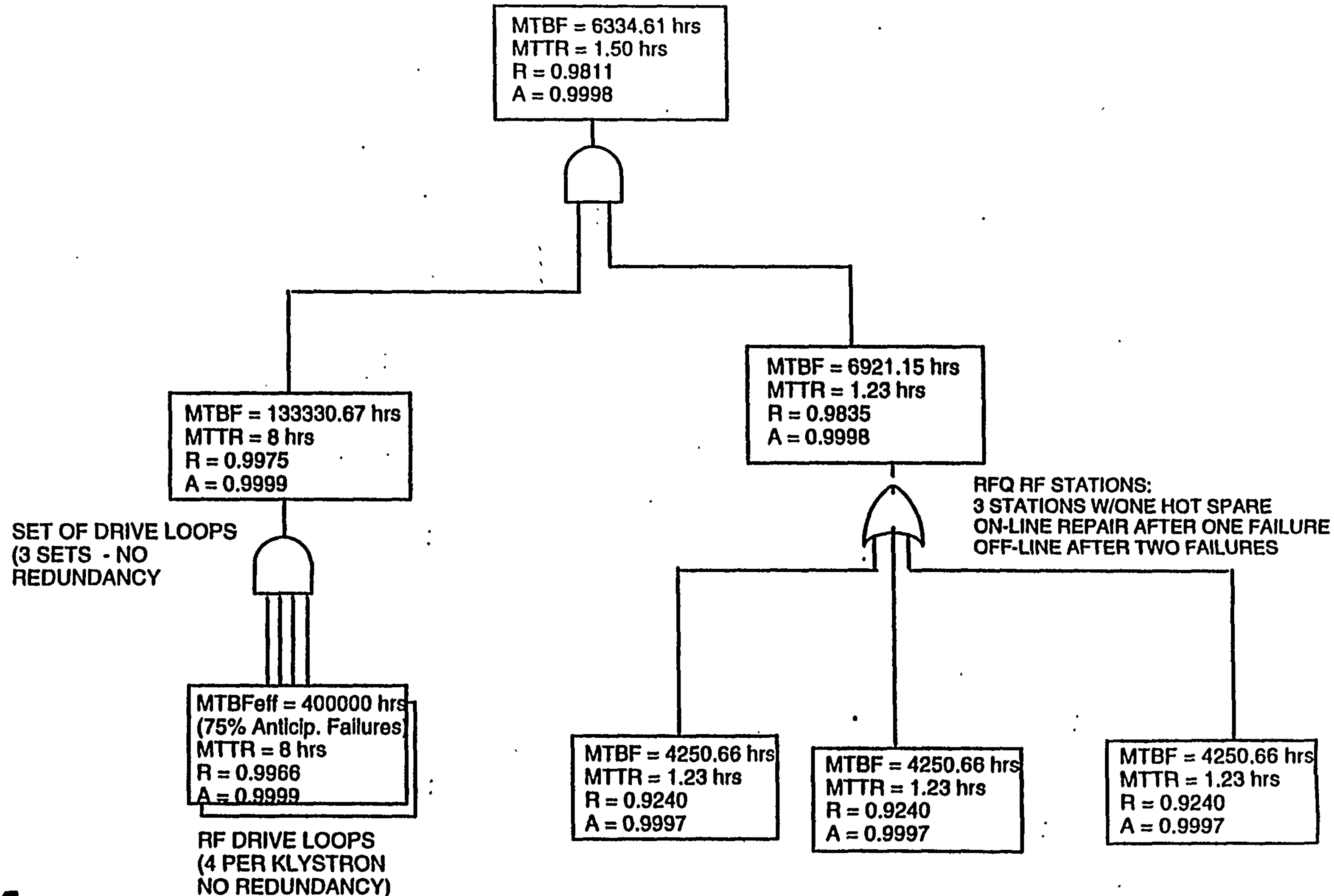
RFQ RF Supermodule - RAMI Model

The RAMI model of the RFQ RF system is shown in the next page. There are three RF stations in the RFQ RF system. The RFQ RF system is assumed to be capable of tolerating a failure of one of the RF stations using the basic RF supermodule arrangement. Morever, repairs of the failed RF station can be performed on line. Only when the second RF station fails before the repair of the spare is completed, does the production have to be stopped. All RF stations are assumed to be on in normal operation. Hence, the RAMI model with hot spares (operational redundancy) is used. The 4-state Markov model is applied. It assumes that the switching time required to isolate the failed spare RF station from the system takes the system off line for 15 minutes. This includes the time necessary to activate a waveguide switch as well as the additional time necessary to ramp the load on the electrical supply grid. In comparison, the time assumed to bring load the grid from the failed state of complete zero, i.e. after the failure of the second RF station in the same supermodule is 30 min. Thus, the RAMI model assumes that a design provision has been made to maintain a large portion of the RF load on the grid during the entire switching operation. As the details of the design become more complete, this assumption may have to be modified. It is expected to have a significant impact on the top level availability estimate due to the large number of RF stations in the system.

RFQ RF Supermodule - RAMI Model (Continued)

The RAMI model of the RFQ RF supermodule also includes a set of RF drive loops (4 per klystron), which represents the entire RF feed assembly including the RF window(s), and the RF coupler. Details of the design for this assembly are not available at the time of this analysis. This element is also very significant in the RAMI estimate for the accelerator since it is present in large quantities (over a thousand if the superconducting linac is included) and there is no on-line repair capability. The MTBF value used in the analysis, of 100,000 hours is consistent with the number estimated for the LAMPF accelerator based on over 20 year of experience. It should be noted, however, that both the power levels and the duty factor are by orders of magnitude smaller for the LAMPF accelerator than those for which the APT drive loops are being designed. Obviously, it is impossible to predict whether the performance required for these elements will be achievable. The currently available statistical sample for such equipment is nonexistent. Only tests can tell how difficult it will be to design such high reliability at the high power and duty factor levels representative of APT.

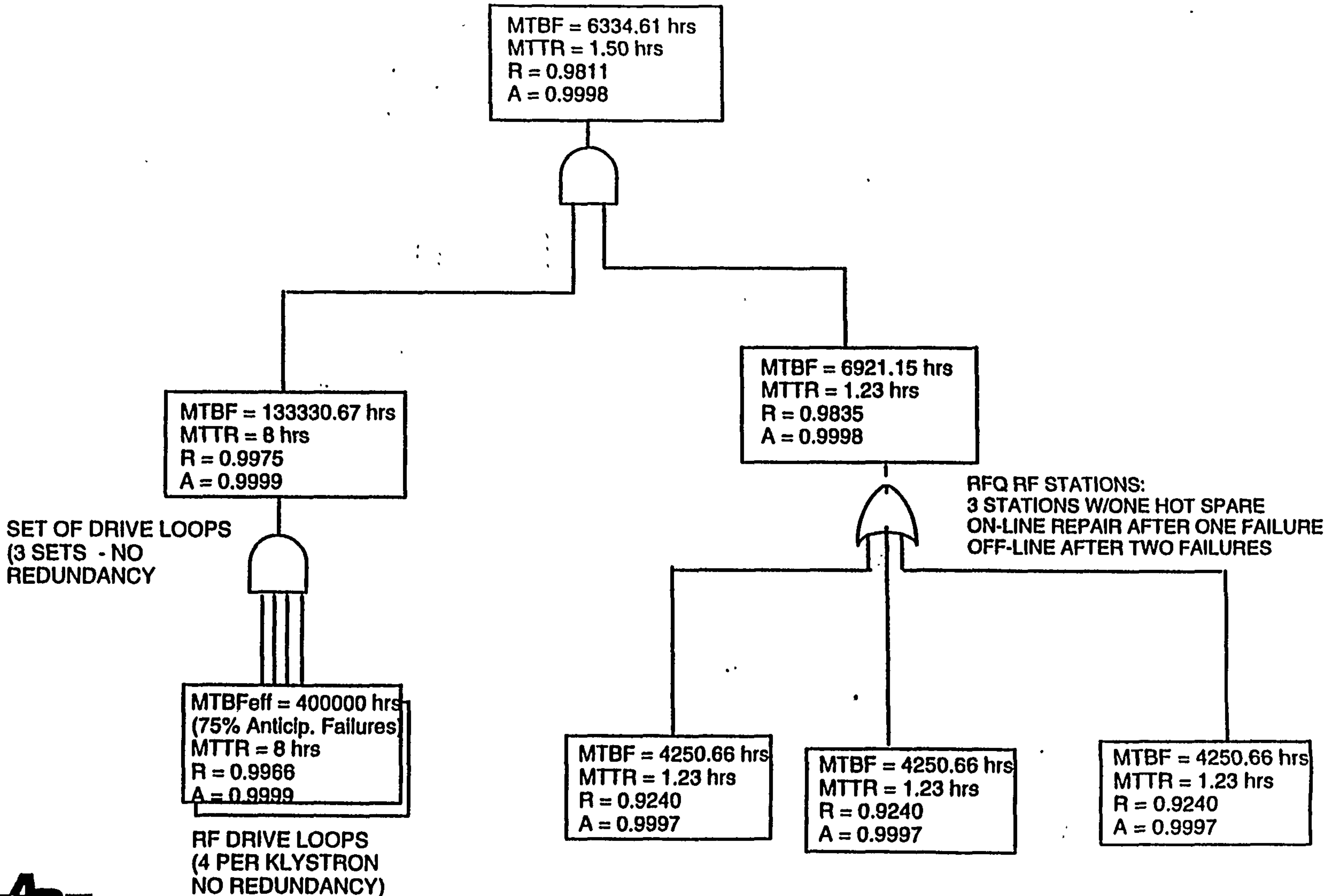
RFQ RF Supermodule - RAMI Model



CCDTL RF Supermodule #1 - RAMI Model

The RAMI models for the CCDTL & CCL supermodules are similar, differing in the number of RF stations. As an example, the CCDTL supermodule number 1 is shown in the next page. Most of the comment about the RAMI modeling approach an d uncertainties made above in reference to the RFQ RF system apply to all the CCDTL and CCL supermodules as well.

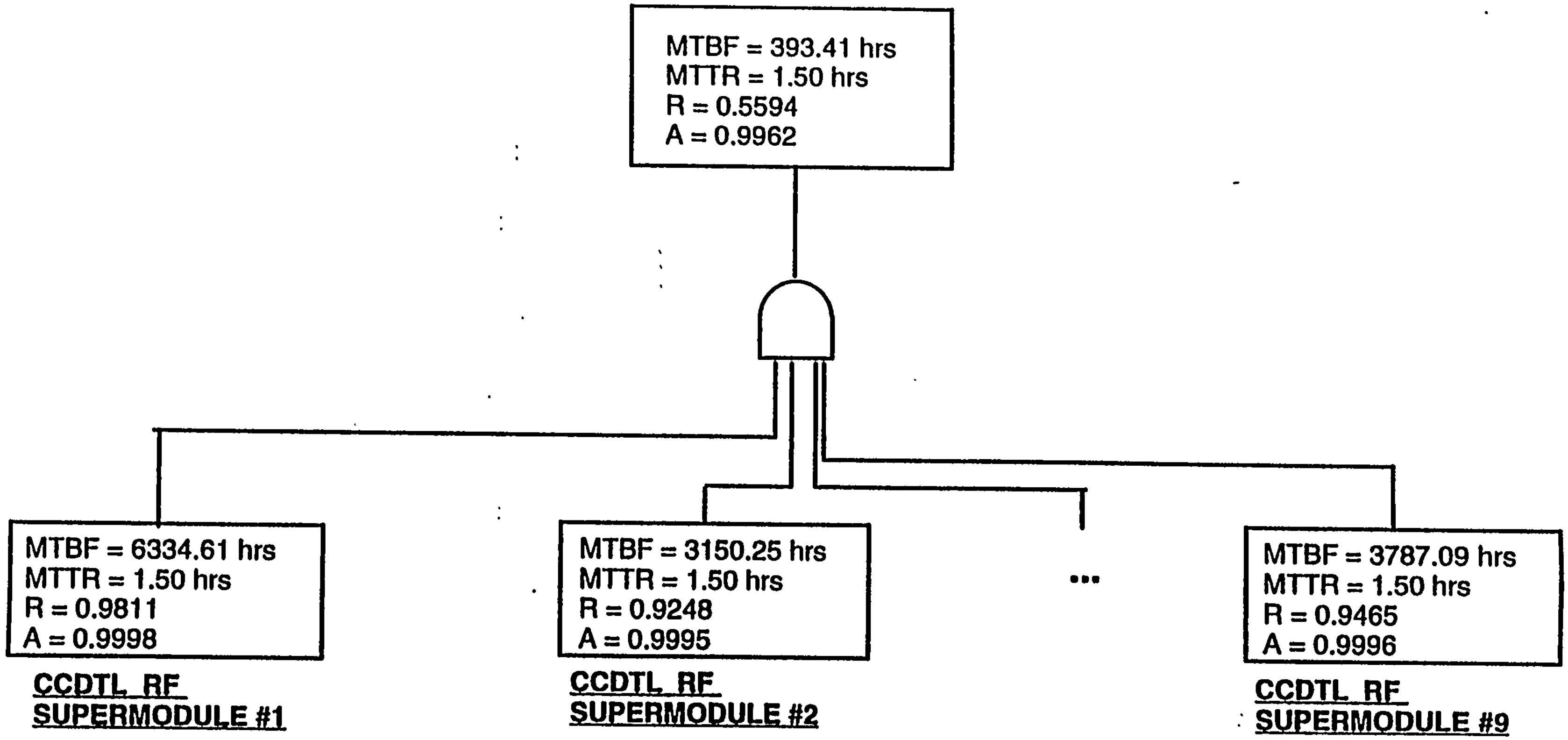
CCDTL RF Supermodule #1 - RAMI Model



7-217 MeV CCDTL/CCL RF System (RT & SC APT Accelerator) RAMI Model

The CCDTL/CCL supermodules are arranged into the Front End CCDTL/CCL RF system in a series topology as shown in the next page.

7-217 MeV CCDTL/CCL RF System (RT & SC APT Accelerator) RAMI Model



SUPERMODULE #	1	2	3	4	5	6	7	8	9
NO. OF RF STATIONS	3	6	7	7	5	5	5	5	5

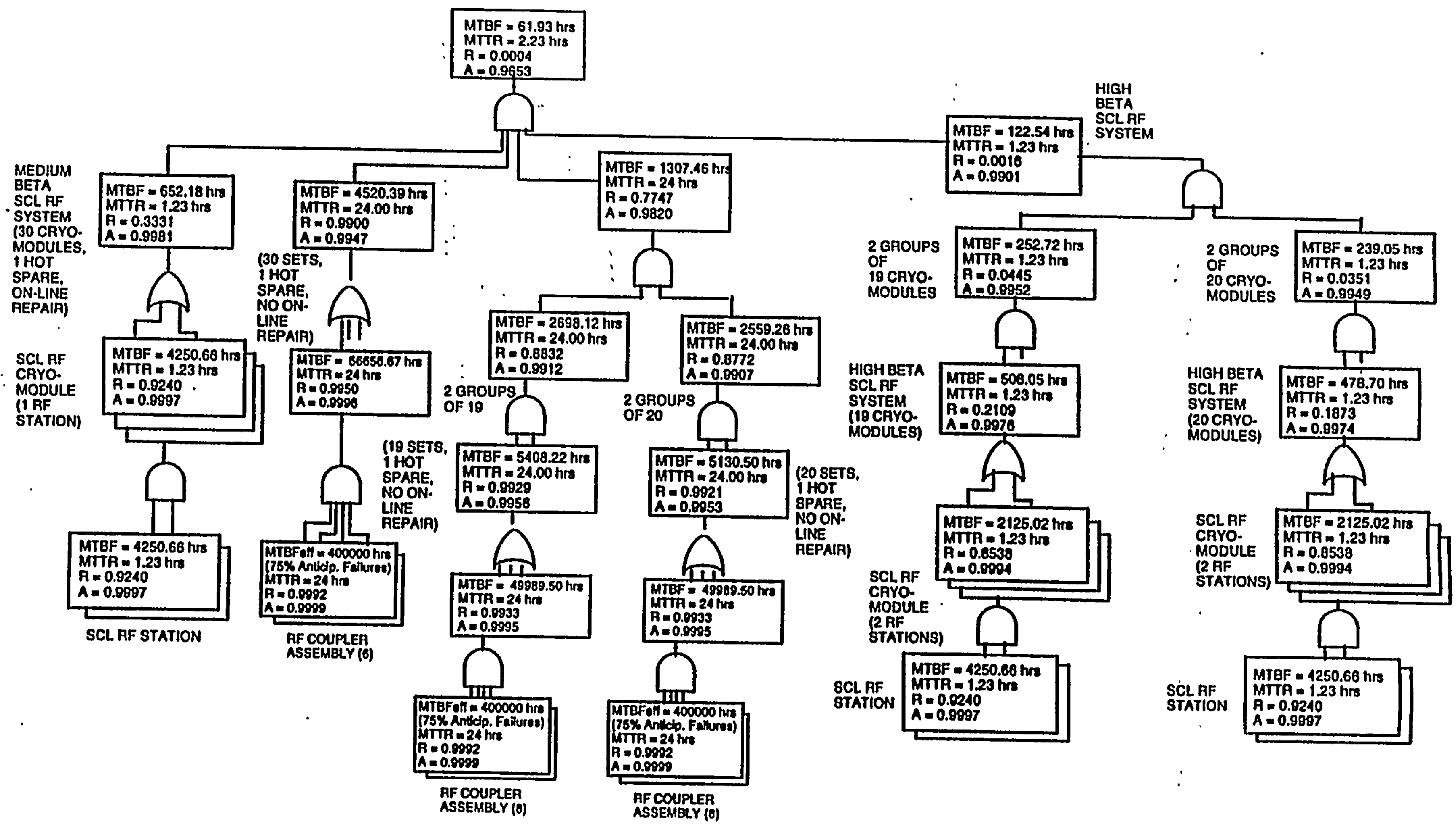
APT Accelerator Production of Tritium

NORTHROP GRUMMAN

217-1780 SCL RF System - RAMI Model

The other major section is the SCL RF system. The RAMI model for the SCL RF system is shown in the next page.

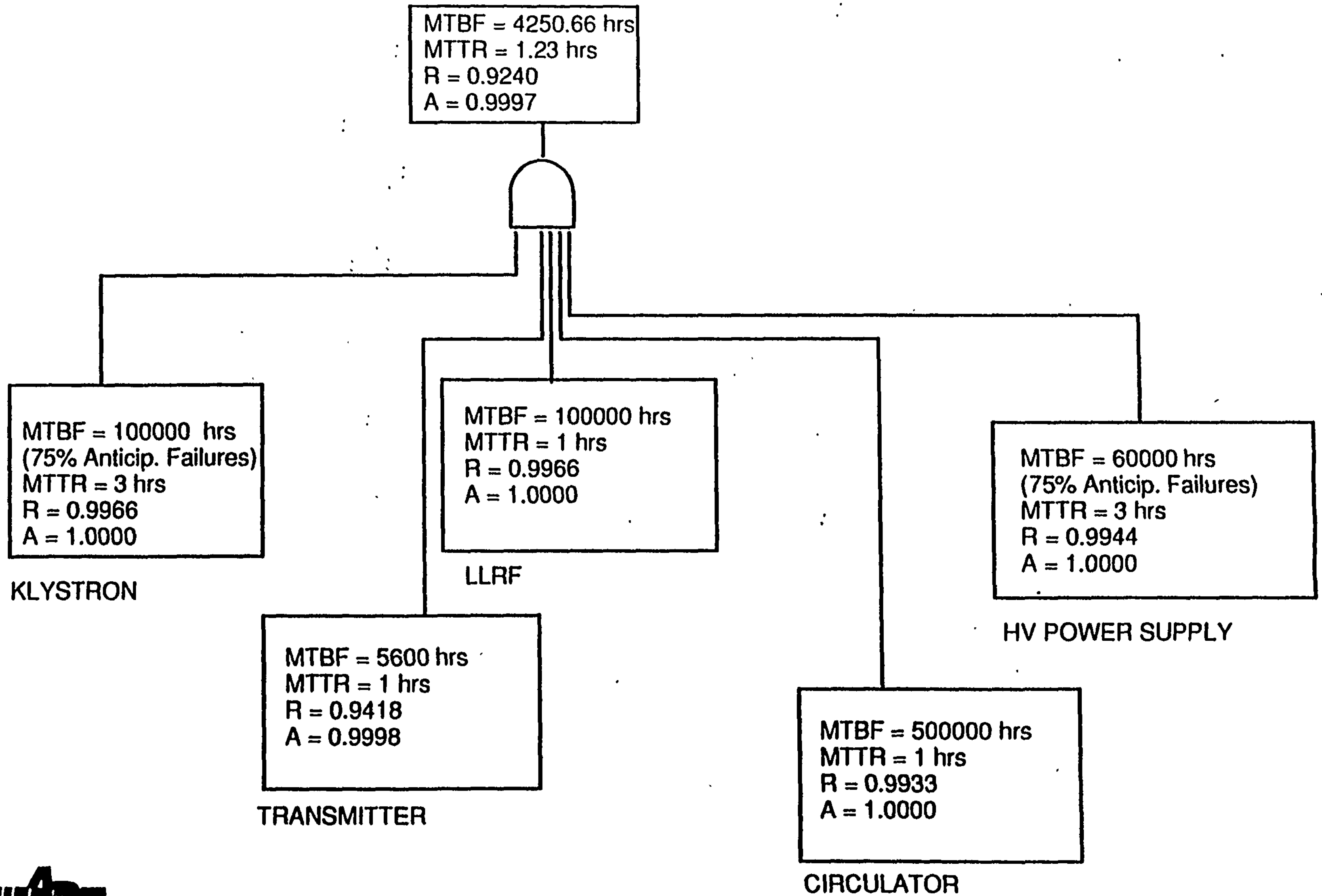
217-1780 MeV SCL RF System - RAMI Model



RF Station - RAMI Model

Each individual RF station includes the klystron, the transmitter, the water cooling, high voltage power supply (HVPS), circulator, and low level RF (LLRF) as shown in the next page. The failure rates used for this model have been supplied by the vendors responsible for these entire assemblies as indicated. The MTTR values are estimated based on prior experience at Los Alamos.

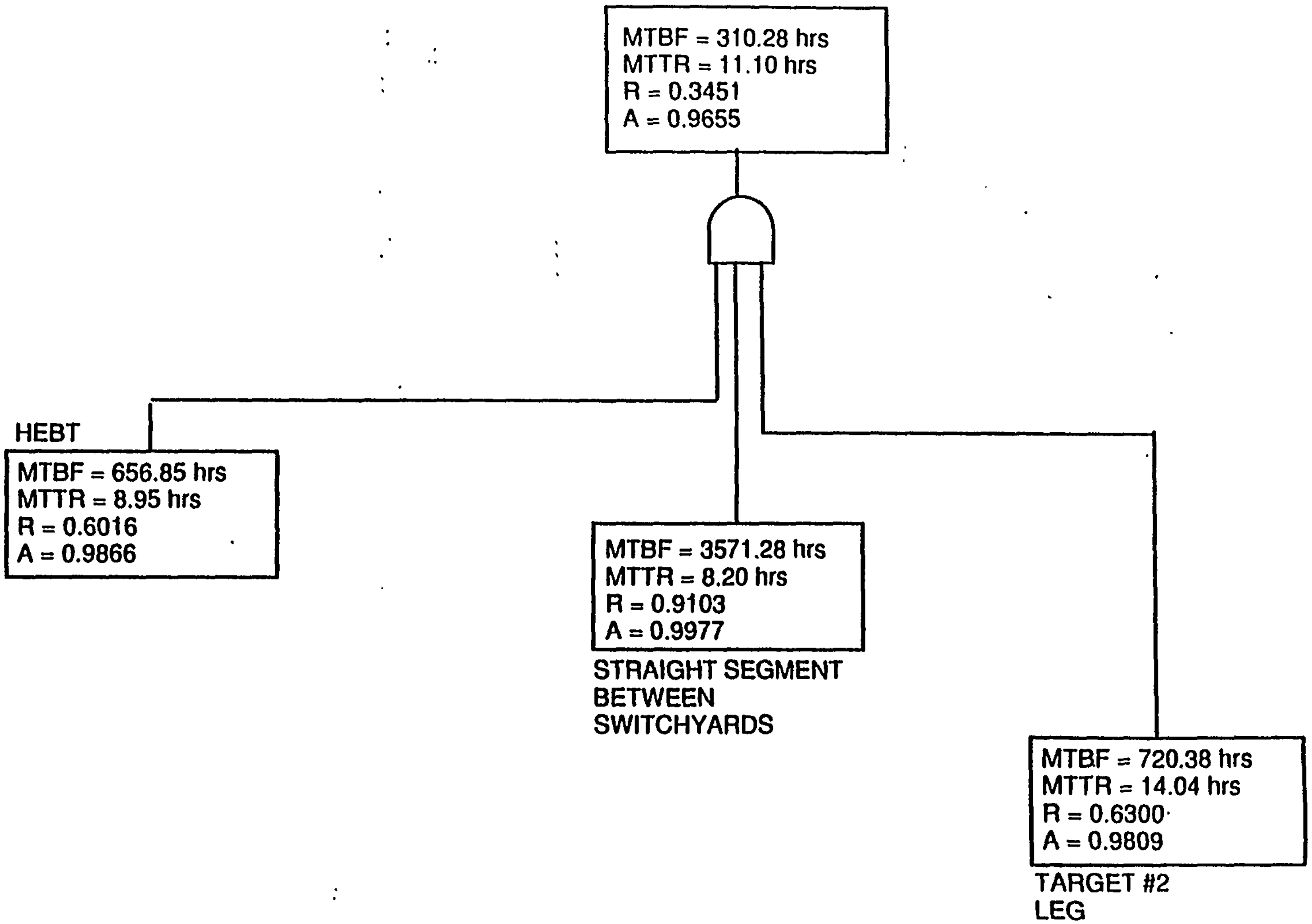
RF Station - RAMI Model



3.4.2.4 HEBT System - RAMI Model

The RAM model of the HEBT system is shown in the next page. It consists of the high energy beam transport (HEBT) itself, the target leg, and the straight segment between the HEBT and the Target Leg. The function of the HEBT System is to transport the beam from the accelerator to the target.

HEBT System - RAMI Model



APT Accelerator Production of Tritium

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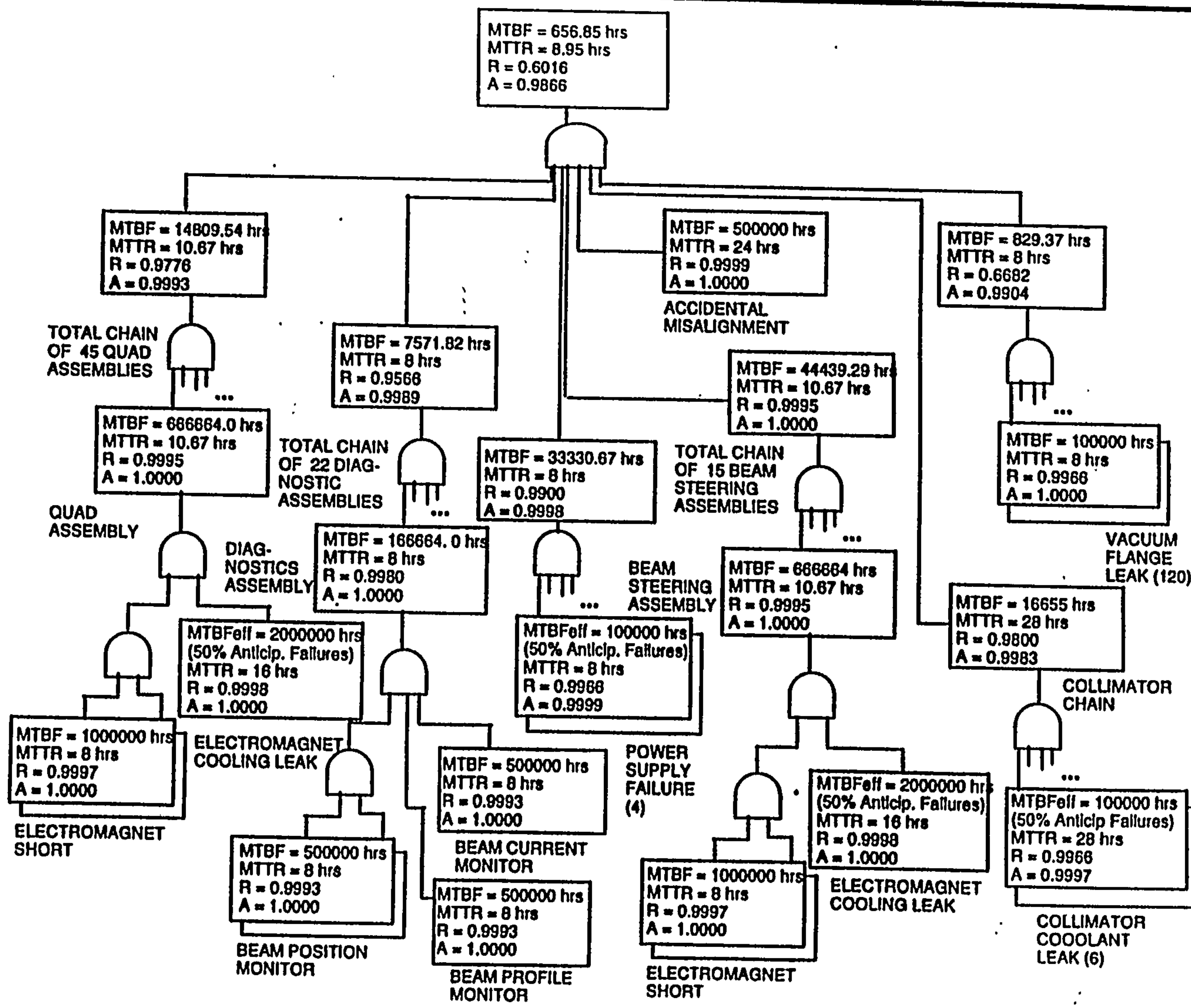
HEBT - RAMI Model

The HEBT consists of a series of 45 quadrupoles in FODO lattice, 22 diagnostics assemblies including each a beam position monitor, a beam profile monitor, and beam current monitor, 15 magnet steering assemblies, magnet power supplies (approximately one per 20 magnets where practical), 120 vacuum flanges (2 per magnet), and a 6 segment beam collimator assembly. The RAMI model of the HEBT is shown in the next page. The failure modes typically encountered in the HEBT components are the coolant (water) leak, electromagnet short, failures of the diagnostics, or magnet power supply, or vacuum leak. In addition, there also exists a possibility of a more global type of failure, involving more than one component, such as, for example, a misalignment of the HEBT optics chain caused by a fork lift truck impact or other such event. As unlikely as such an event may be, the long MTTR associated with bringing the HEBT back into alignment warrants its inclusion into the RAMI budget.

HEBT - RAMI Model



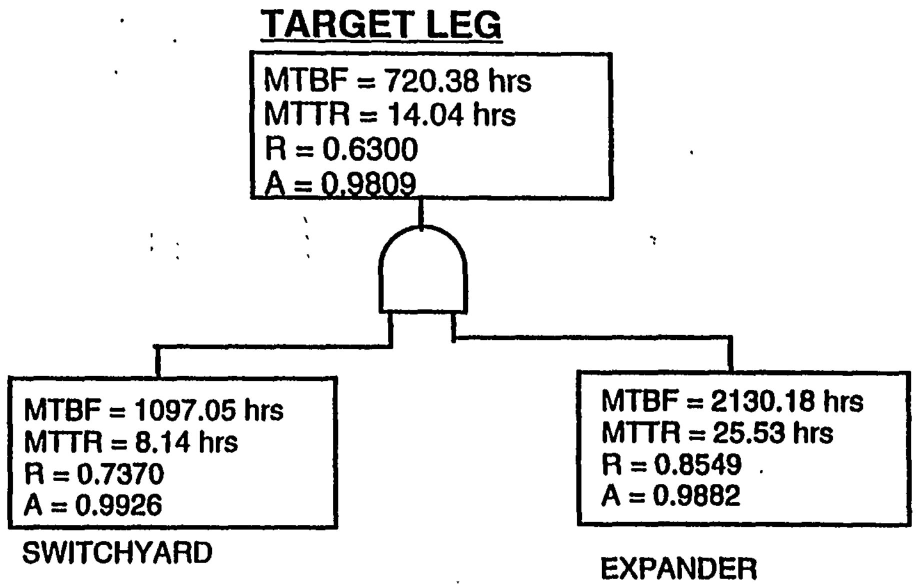
Accelerator Production of Tritium

NORTHROP GRUMMAN

Target Leg - RAMI Model

The target leg consists of the switchyard and the expander assemblies. The RAMI model of the target leg is shown in the next page. The failure modes typically encountered in the target leg components are the same as in the HEBT: the coolant (water) leak, electromagnet short, failures of the diagnostics, or magnet power supply, or vacuum leak, as well as the misalignment.

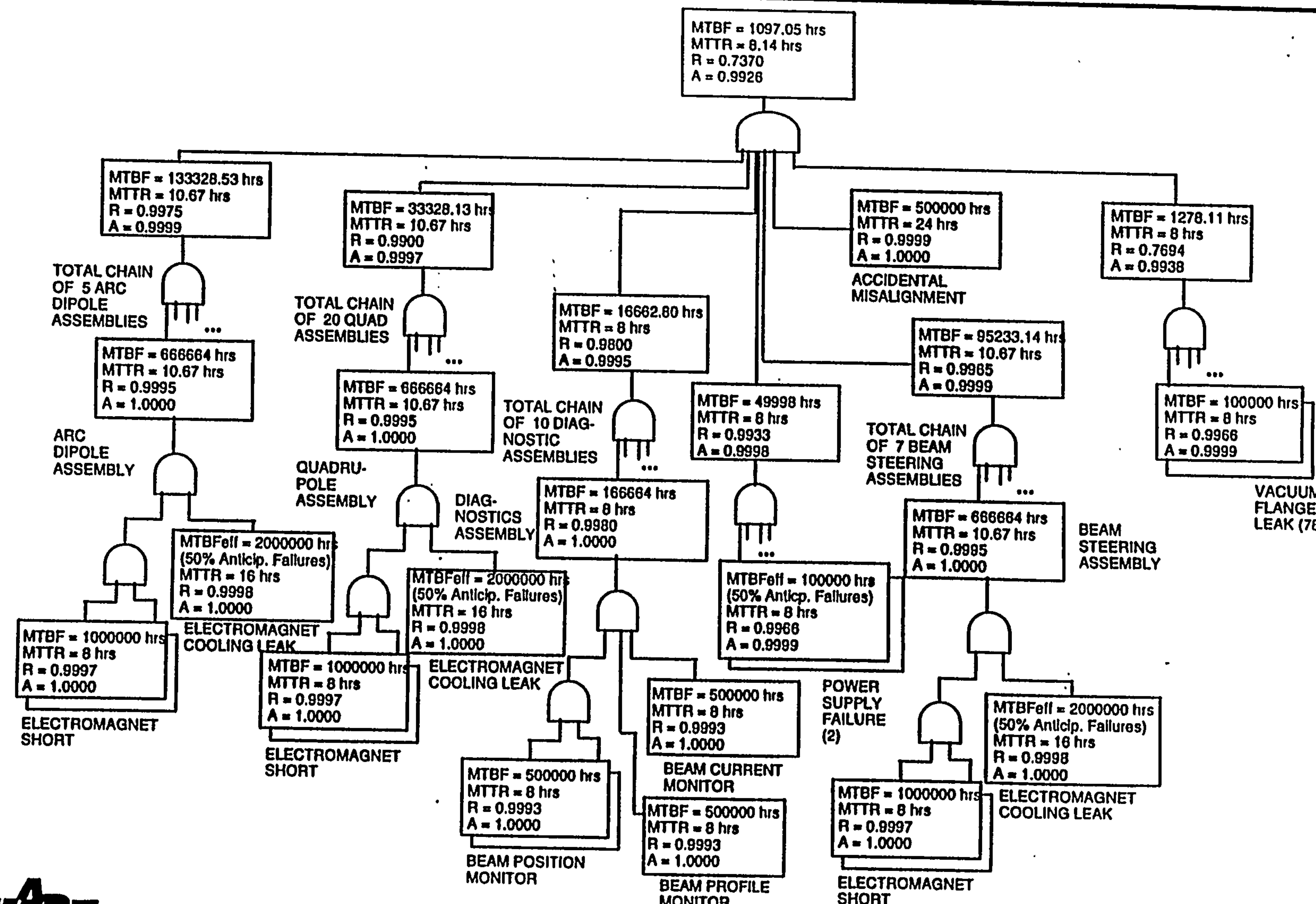
Target Leg - RAMI Model



Target Leg Switchyard - RAMI Model

The RAMI model of the target leg switchyard is shown in the next page.

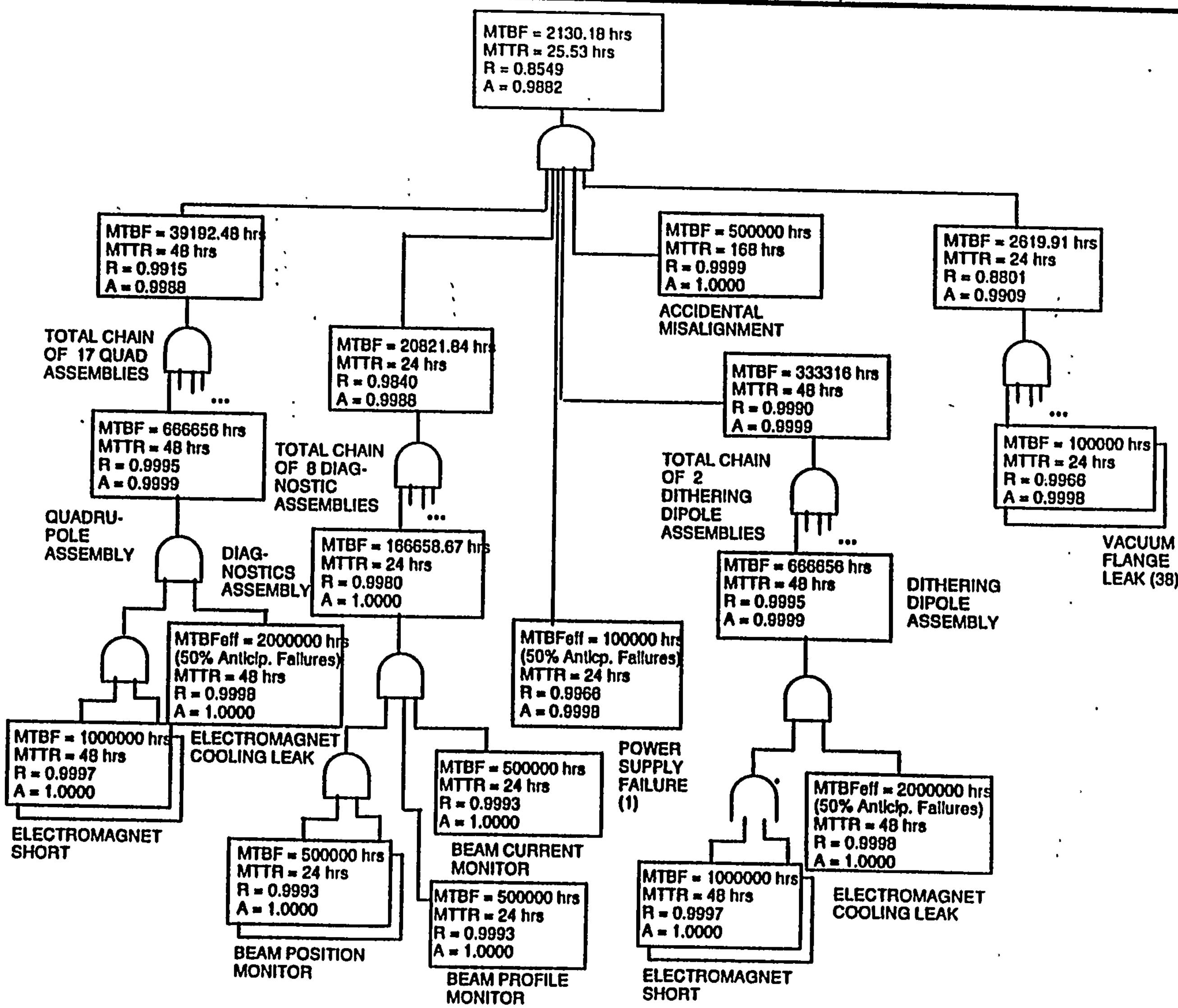
Target Leg Switchyard - RAMI Model



Target Leg Expander - RAMI Model

The RAMI model of the target leg expander is shown in the next page. The target leg expander consists of 17 quadrupoles in a FODO lattice, 2 dithering dipoles, 2 diagnostic assemblies, and the power supply.

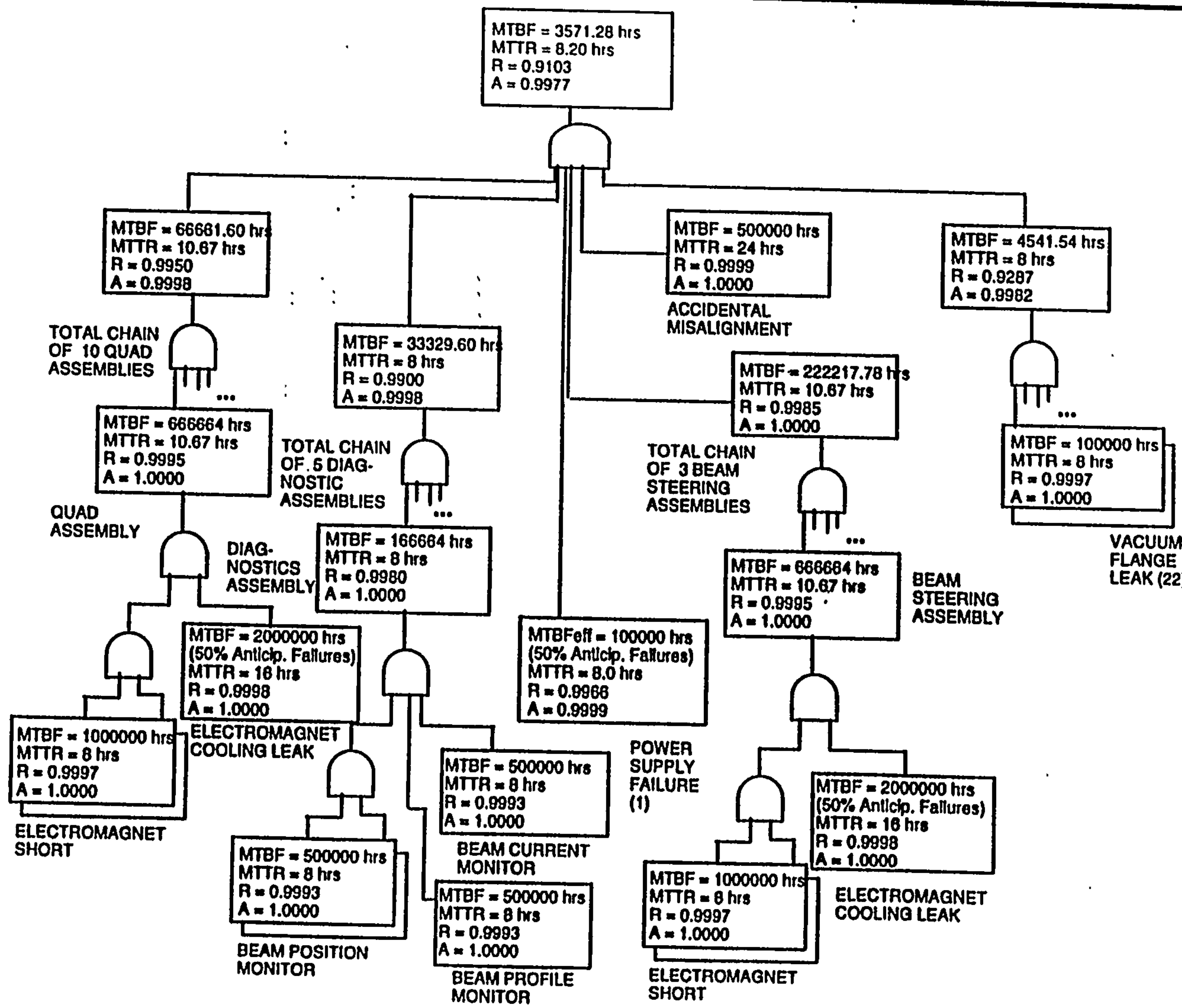
Target Leg Expander - RAMI Model



Straight Segment Between Switchyards - RAMI Model

The straight segment between the switchyards consists of a series 10 quadrupoles in a FODO lattice, 5 diagnostics assemblies including each a beam position monitor, a beam profile monitor, and beam current monitor, 3 magnet steering assemblies, 1 magnet power, and 26 vacuum flanges (2 per magnet). The RAMI model of the straight segment section is shown in the next page.

Straight Segment Between Switchyards - RAMI Model



3.4.3 Summary of the SC APT Accelerator RAMI Budget

This table summarizes the top level RAMI budget for major subsystems, including the injector, linac, RF system, and HEBT.

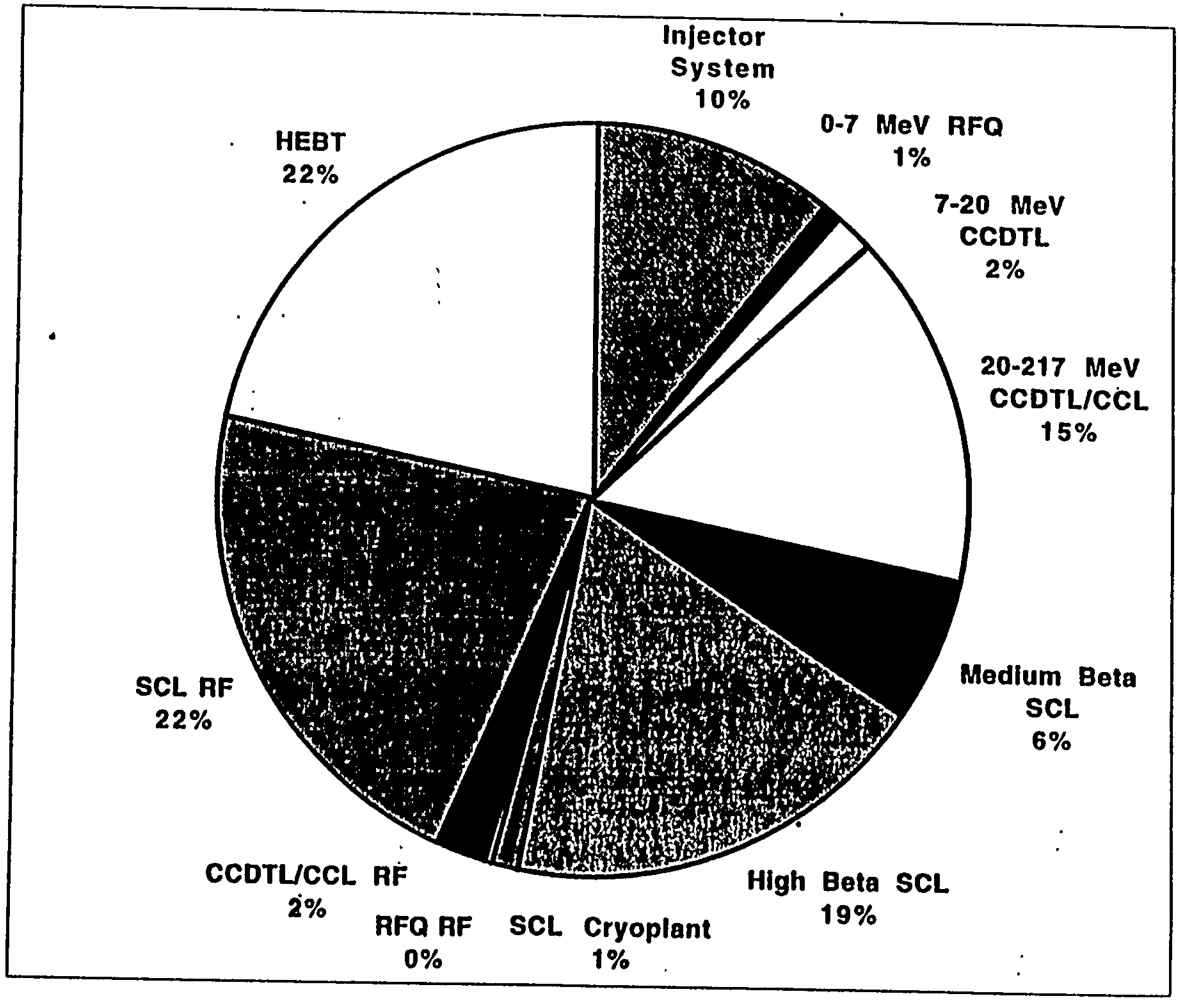
Summary of the SC APT Accelerator RAMI Budget

System	Required Subsystem Steady State Availability	Required System Steady State Availability
Ion source	0.984237	
LEBT	0.998994	
Injector System		0.966773
RFQ	0.998601	
7-20 MeV CCDTL	0.997328	
20-217 MeV CCDTL & CCL	0.975724	
SCL Medium Beta Section	0.990197	
SCL High Beta Section	0.970033	
SCL cryoplant	0.998265	
SC Linac		0.931775
RFQ RF System	0.999763	
Front end CCDTL/CCL RF System	0.996194	
SCL RF System	0.965287	
Global RF controls	0.999840	
SCRF System		0.961232
HEBT	0.986551	
Straight segment	0.997710	
Target leg	0.980876	
HEBT, switchyard & expanders		0.965468
APT SC System		0.850236
Availability Goal (minimum)		0.85

System Unavailability Drivers

System unavailability drivers are clearly identified in the next page which shows a pie chart of the percentages each subsystem contributes to the overall unavailability. Clearly, the SCL, the HEBT, and the RF system are comparable in importance.

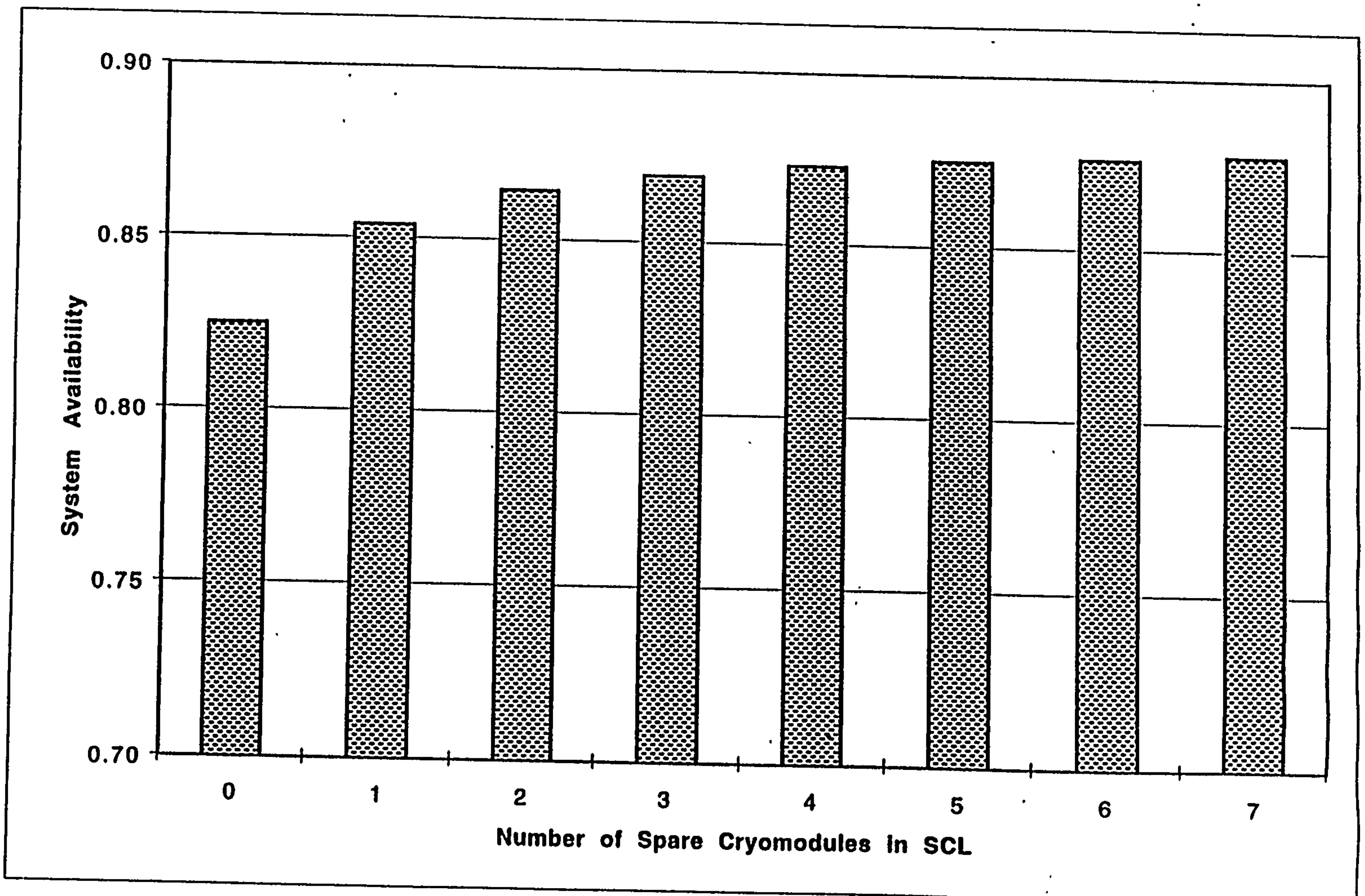
System Unavailability Drivers



The Required Number of Spare Cryomodules

A question of considerable importance is the number of required spare cryomodules. In the analysis shown in the next page, the SCL was assumed to consist of a series of identical cryomodules and the number of tolerable failures is varied. The availabilities are somewhat overestimated because the tolerable failures are allowed even if they are contiguous, i.e. the last result allows for 7 failed cryomodules in a row. Even with this optimistic approach, however, the result clearly shows that at least 2 spares are indeed required to reach a decent level of system availability. With 5 spares, the slope of the curve begins to level off. 5 spares have been used in the design.

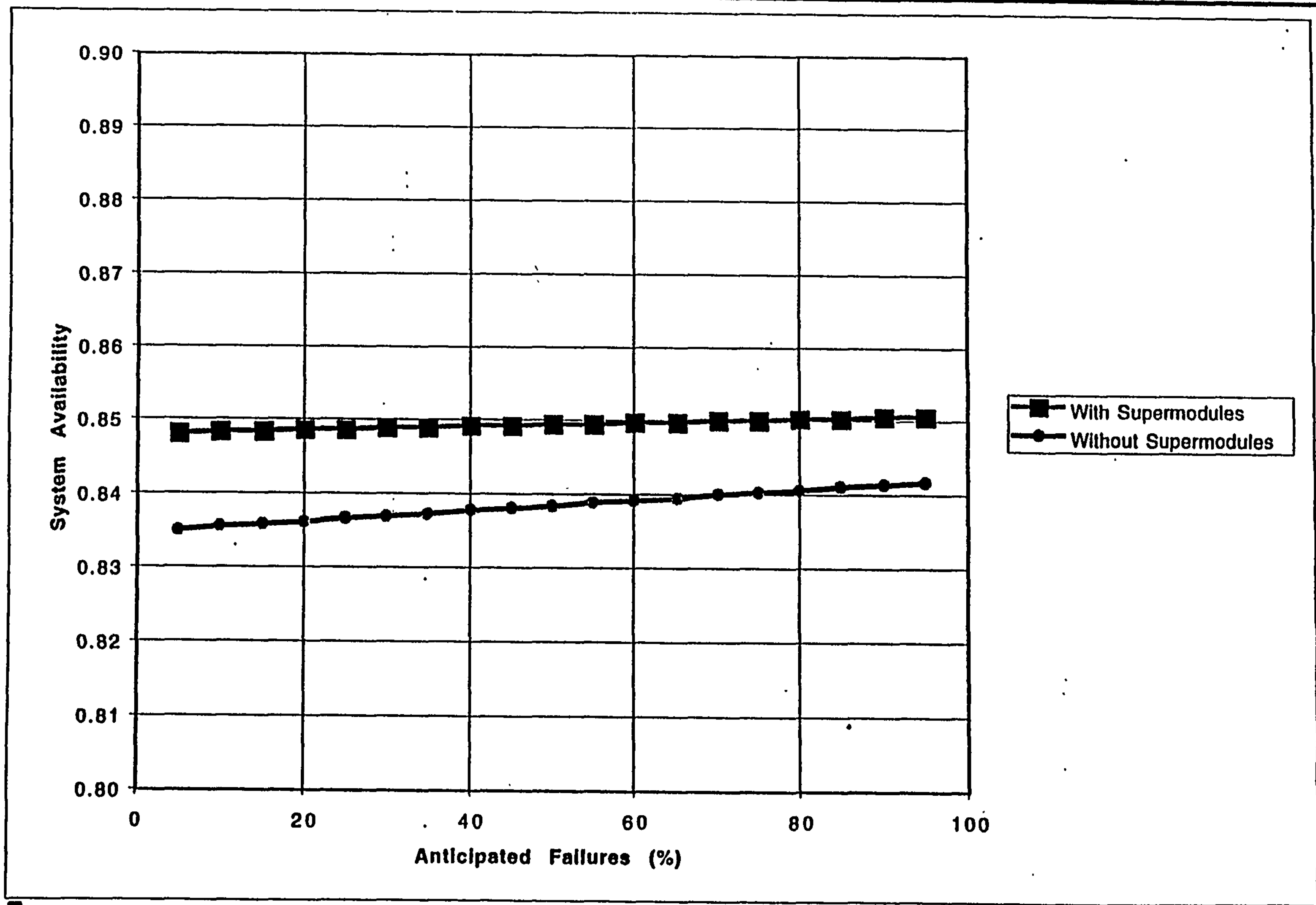
The Required Number of Spare Cryomodules



Effect of Anticipated Failures of the Klystron on System Availability

Another important issue arises in the design of the RF system. The question is about the effectiveness of the diagnostics for prediction of anticipated failures of the klystron in the RF station and a possibility of using this option as a replacement for the supermodules. The results of an analysis to investigate this question are illustrated here. The two curves represent the system availability as a function of the percent of anticipated failures of the tube, which would in some way be proportional to the quality, and presumably cost, of the tube diagnostics. The top curve shows this dependence for the design incorporating the supermodule option and the lower curve the design without it. It is clear that the diagnostics cannot replace the improvement in availability provided by the supermodules, no matter what their quality.

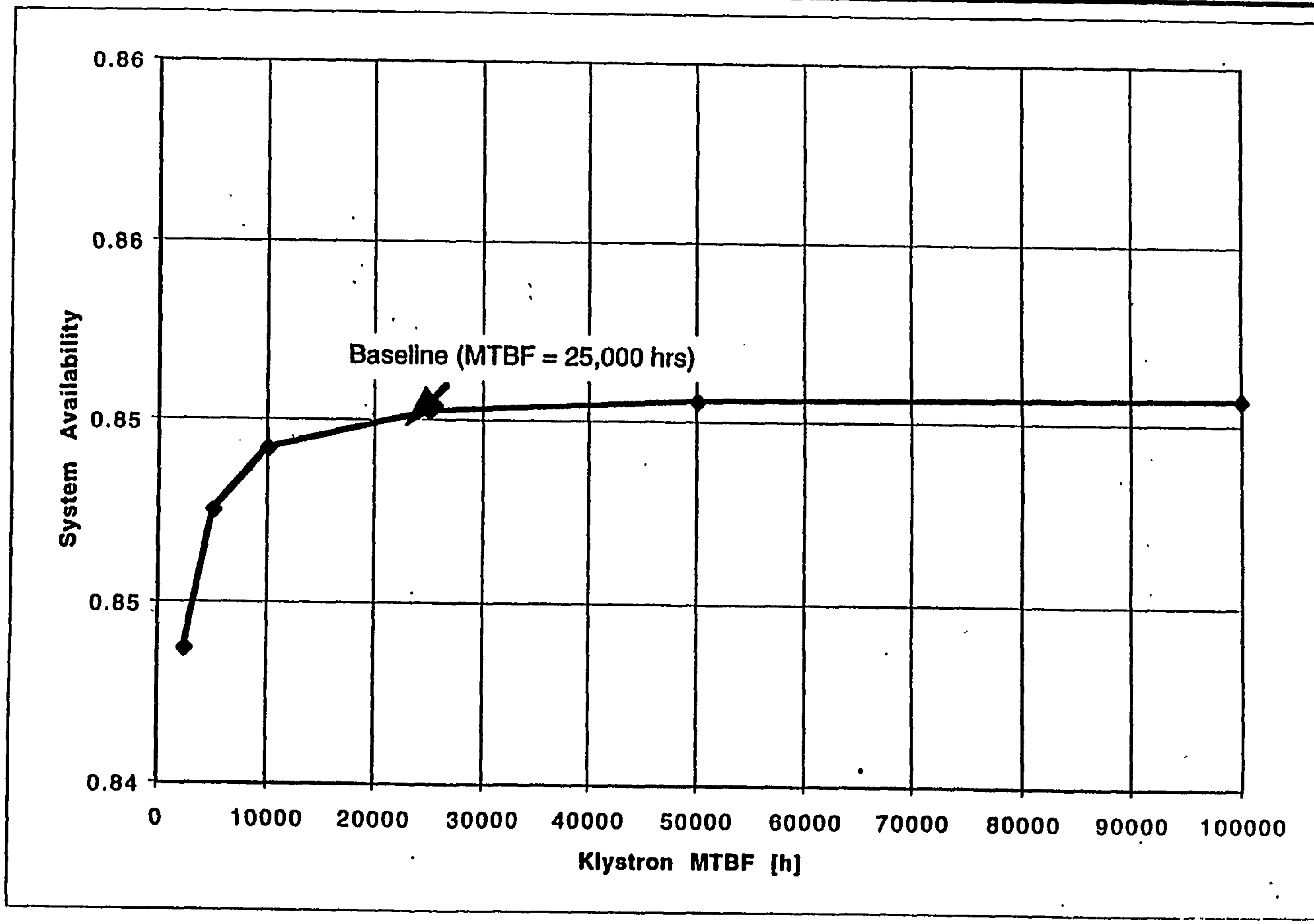
Effect of Anticipated Failures of the Klystron on System Availability



Effect of Klystron MTBF on the Top Level System Availability

In fact, the question arises then why is it so? The answer turns out to be relatively simple in that the RF station availability is really limited by its components other than the klystron. The curve illustrates this point. No matter how high the MTBF of the klystron is raised with the failure anticipation by means of improved diagnostics, the overall system availability is flat, provided that the initial klystron MTBF is at least 25,000 hrs. This result is clearly of interest to the RF system designers since it indicates that unless the other components of the RF station are significantly improved, there is no reason to spend valuable resources in improving the klystron.

Effect of Klystron MTBF on the Top Level System Availability

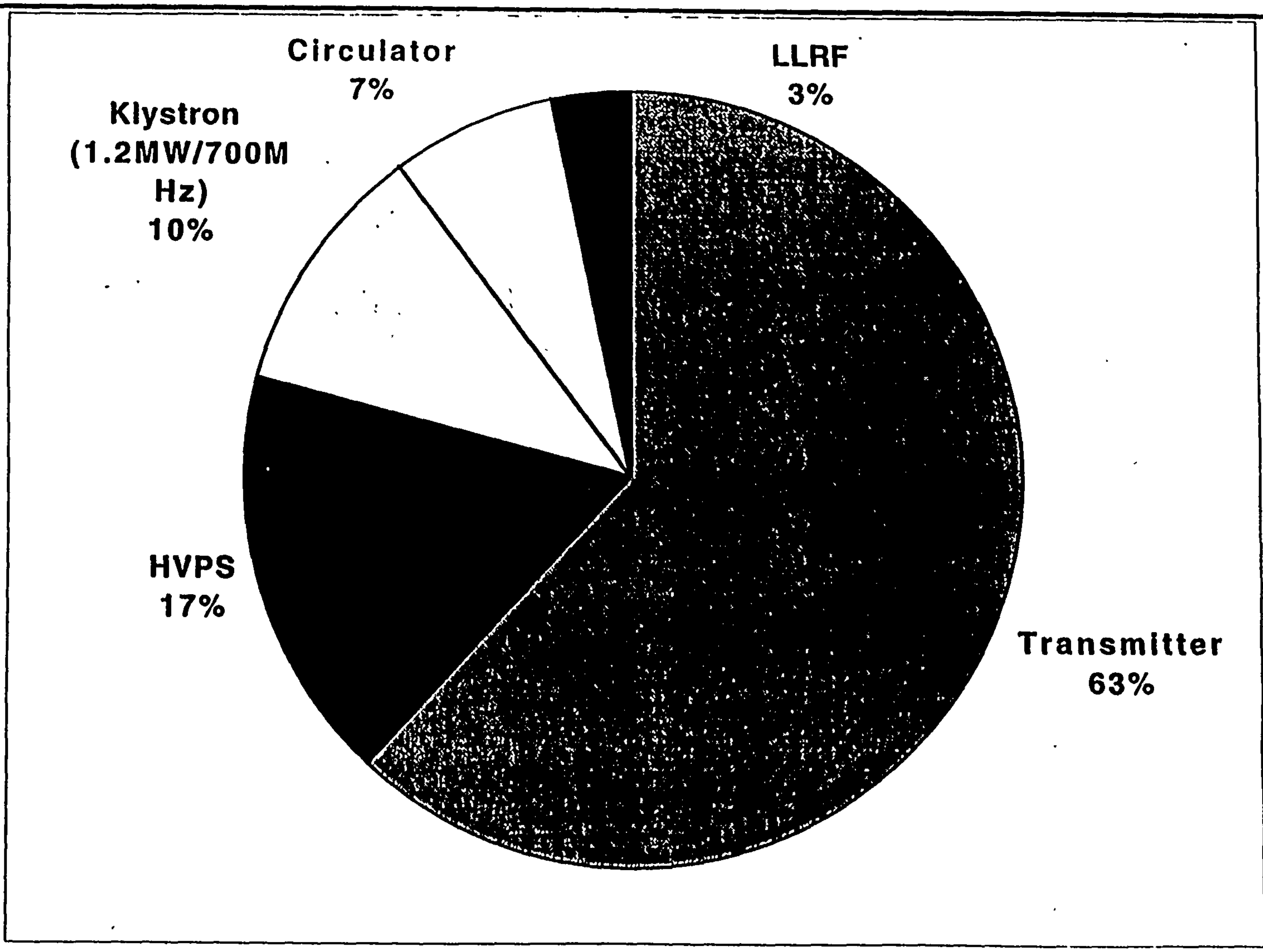


RF Station Unavailability Contributions

In order to see which parts of the RF station are the unavailability drivers and therefore would be the most cost effectively improved to raise the RF station availability, we plotted the unavailability contribution of each part of the RF station as a percentage of the total. Clearly, the water cooling, and then the HVPS, and the Transmitter are the main factors as can be seen in here. The Klystron itself comes in the fourth place.

Although the above analyses point to the conclusion that klystron diagnostics for prediction of anticipated failures will not be able to improve system availability by increasing the effective MTBF in a considerable manner, one should not make a hasty decision of dropping them from any further consideration. It should be remembered, that effective diagnostics will be instrumental in reducing the MTTR, which could be driven by the time it takes to identify the faulty element of the system. Other types of diagnostics may, however, be required for this purpose.

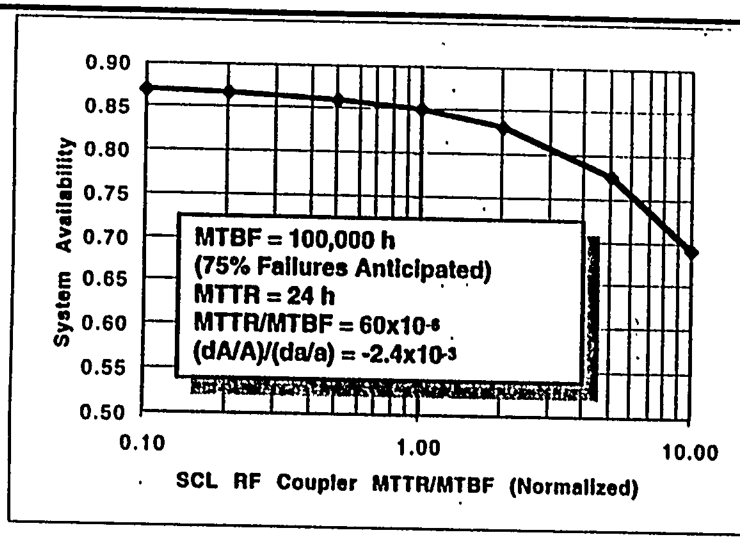
RF Station Unavailability Contributions

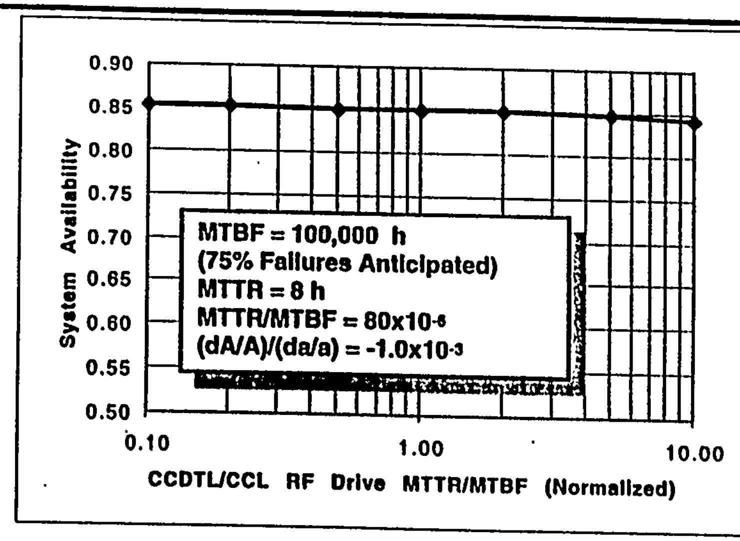


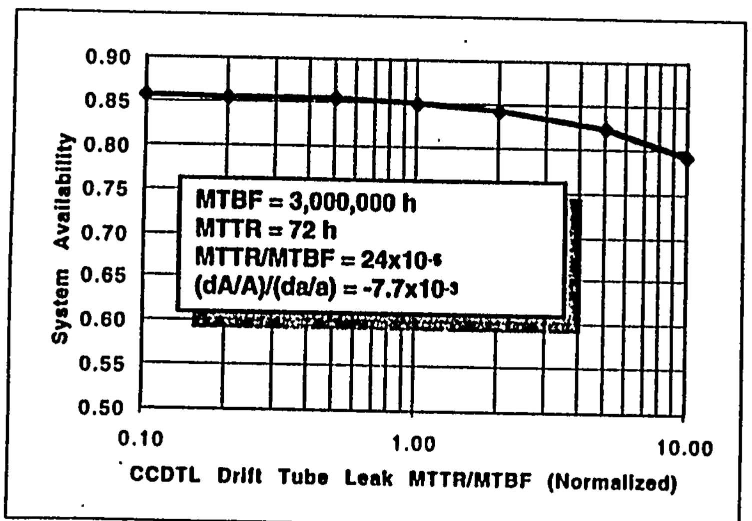
System Availability Sensitivity for Critical Components - I

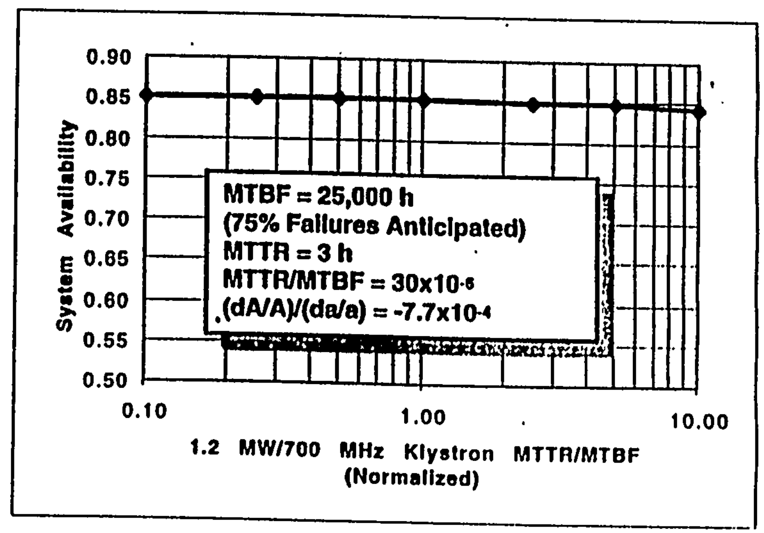
The analyses of the RAMI model can be very valuable if presented in a nondimensionalized form covering a range of parameter values. As an example of this type of result, we have chosen a number of components and plotted the system availability as a function of the MTTR/MTBF ratio varied over a range spanning two decades. This is illustrated in the next page, where in order to improve the clarity of the presentation, we have plotted the system availability curves against the ratio MTTR/MTBF normalized with its value for the baseline model which is provided in each case. With this type of graph, the effects of the variation in either MTTR or MTBF of the given components are clearly visible. The RF coupler is definitely an important driver of system availability.

System Availability Sensitivity for Critical Components







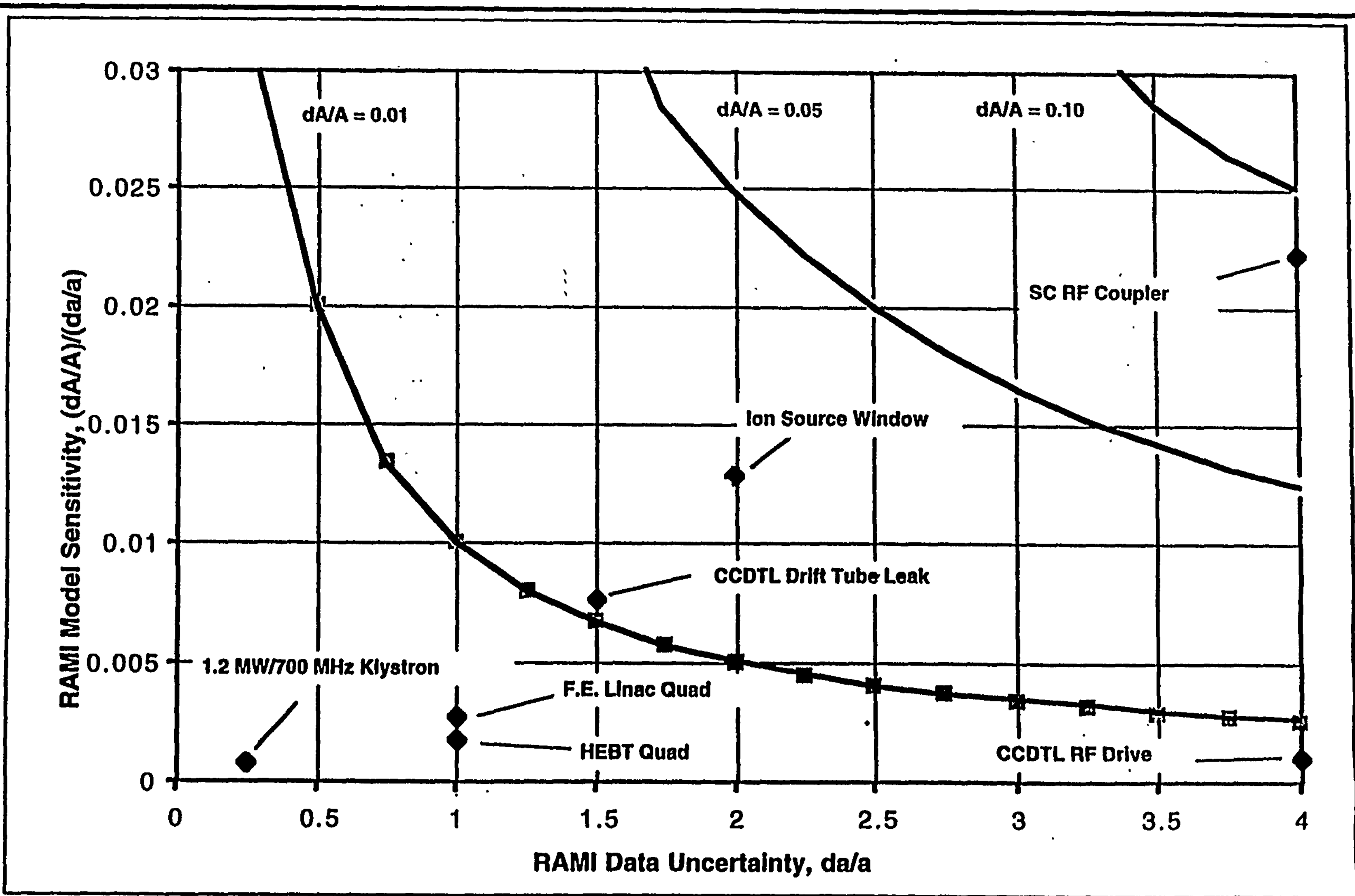


System Availability Sensitivity to Data Uncertainty

The values of the derivative of the system availability with respect to the variation of the MTTR/ MTBF ratio (normalized) presented in the previous page can be used to examine the sensitivity of the RAMI model to the uncertainty in the input parameters. This is illustrated in the next page where the relative change in system availability has been plotted as a function of the data uncertainty. Clearly, the SCL RF coupler is an example of a component with high data uncertainty driving the reliability of the system. The present analysis is by no means a complete review of all the system drivers for the sensitivities were evaluated only for a sample of items. Additional analyses will be required to provide a more exhaustive review.

The diagram clearly identifies two strong drivers: the SCL RF coupler, and the ion source RF window. Note that the RAM model sensitivity to the 1 MW/ 700 Mhz klystron is low due to the effects of the redundancies in the RF system, introduced by means of supermodules in the room temperature linac and failure tolerability in the SC linac.

System Availability Sensitivity to Data Uncertainty



Estimation of the Klystron MTTR

There are many different corrective maintenance procedures to consider for the system as complex as the APT facility. In fact, there will be one for each failure mode of every critical component. Detailed analysis and planning for each one of these will have to be performed during the detail design phase. As an example, the sequence of tasks required to replace a faulty klystron tube, together with the corresponding times (in minutes) is shown in the table on the next page.

The resulting 140 min. were augmented by an additional 40 minutes to account for the additional time required for notification of the maintenance staff, their access to the location, fault identification, search for tools and spare parts, etc. Based on these considerations, the klystron MTTR of 3 hrs was used in the present availability allocation budget. A confirmation of these numbers will be required through more detailed time and motion studies.

While these estimates cannot replace real statistics which may actually be quite difficult to collect unless careful tracking of maintenance operations is carried on for the initial years of the facility's life, a good designer can minimize MTTR's by paying special attention to those aspects of the design which influence them: design for accessibility, strategic placement of the spare parts warehouse with respect to the facility, ease with which the parts are located in the warehouse, and the built-in diagnostic systems allowing for a fast fault identification.

Estimation of the Klystron MTTR

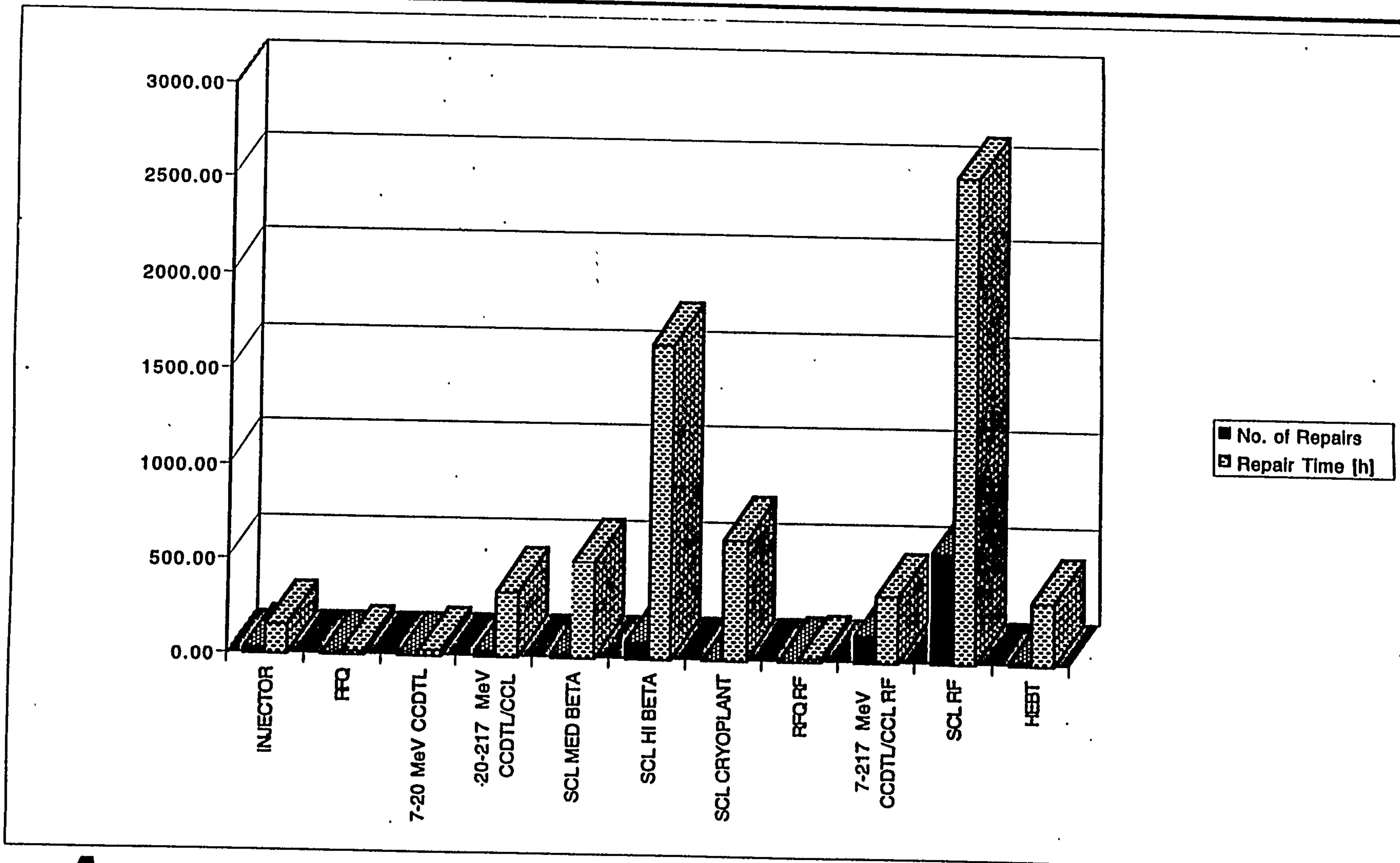
	Step	Time (min.)
1	Shutdown RF station	5
2	Depressurize waveguide	5
3	Disconnect interfaces to tube	30
4	Extract tube & replace with new tube	30
5	Reconnect tube interfaces	30
6	Repressurize waveguide	5
7	Verify coolant line and electrical connections	10
8	Perform turn on sequence for RF station	15
9	Confirm RF adequate system performance	10
	Total	**140**

3 HOURS (180 minutes) USED IN THE MODEL

Predicted Repair Frequencies Per Subsystem

This histogram illustrates the predicted average annual number of replacements and the estimated average annual repair time per subsystem. It should be noted that the actual number of failures and the repair time in any given year will differ from these statistical averages. It is also noted that in order to obtain the total numbers of spare parts estimates, the numbers estimated here for the corrective maintenance have to be added to the numbers of replacements of the same item in the scheduled maintenance program, since the values shown in the figure represent only the replacements needed to correct for the random failures.

Predicted Repair Frequencies Per Subsystem



Normal Conducting System (2 kg Option) - Availability Requirements Summary

For the normal conducting system with 1300 Mev/100 mA, the production rate is scaled from the 0.000479 kg/hr to 0.000335 kg/hr. Also, for this system, the annual planning quota of 2 kg is used, resulting in 5973 hrs of production time requirement. With no change in the scheduled maintenance plan, the scheduled operation still remains at 7752 hrs, and the required inherent availability of the entire APT facility becomes 0.7705. After breaking it down into individual subsystems, and without changing the allocations to the target blanket and the balance of plant, the accelerator availability allocation becomes 0.8300.

Normal Conducting System (2 kg Option) - Availability Requirements Summary

MACHINE CAPABILITY:

Beam Energy (MeV)	1300		
Beam Current (mA)	100		
Production Rate (kg/hr)	0.000335	2.93 (@100%)	2.20 (@75%)
Planned Annual Output Quota (kg)	2		

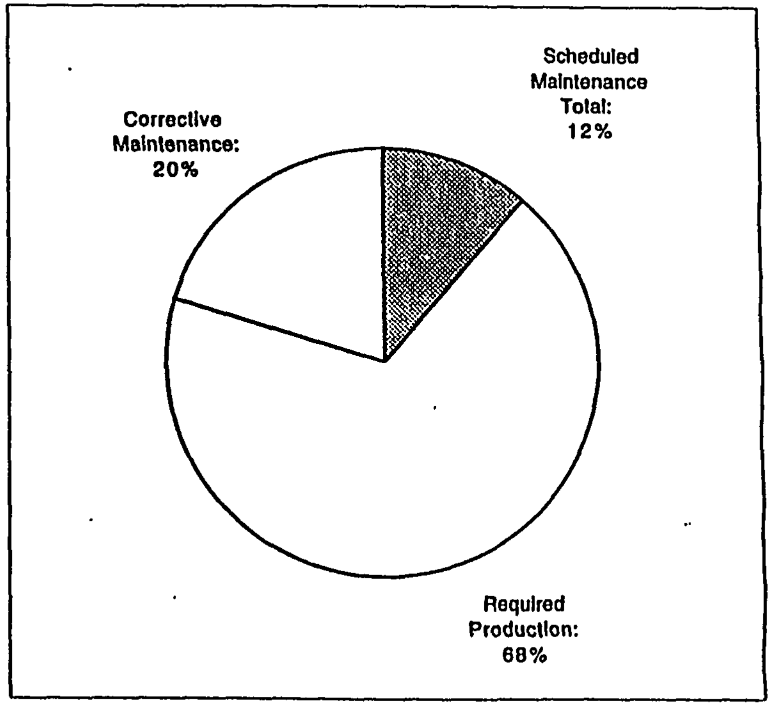
SCHEDULED MAINTENANCE	TOTAL HOURS	TOTAL DAYS	YEAR FRACTION
Scheduled Maintenance Total:	1008	42.0	0.1151
Scheduled Operation:	7752	323.0	0.8849
Required Production:	5973	248.9	0.6818
Corrective Maintenance:	1779	74.1	0.2031

INHERENT AVAILABILITY:

		REQUIREMENTS	ALLOCATION
NC Accelerator		0.8300	0.8591
Target/Blanket		0.9561	0.9561
Tritium Extraction		1.0000	1.0000
Balance Of Plant		0.9730	0.9730
Reserve	0%	0.9978	1.0000
Total APT Plant		0.7705	0.7992

NC APT PRODUCTION AS ALLOCATED (kg): 2.07

Annual Production & Maintenance Budget



Normal Conducting System (3 Kg Option) - Availability Requirements Summary

- For the normal conducting system with 1300 Mev/136.5 mA, the production rate is scaled from the 0.000479 kg/hr to 0.000457 kg/hr. Also, for this system, the annual planning quota of 3 kg is used, resulting in 6563 hrs of production time requirement. With no change in the scheduled maintenance plan, the scheduled operation still remains at 7752 hrs, and the required inherent availability of the entire APT facility becomes 0.8467. After breaking it down into individual subsystems, and without changing the allocations to the target blanket and the balance of plant, the accelerator availability allocation becomes 0.9100.

Normal Conducting System (3 Kg Option) - Availability Requirements Summary

MACHINE CAPABILITY:

Beam Energy (MeV)	1300		
Beam Current (mA)	136.5		
Production Rate (kg/hr)	0.000457	4.00 (@100%)	3.00 (@75%)
Planned Annual Output Quota (kg)	3		

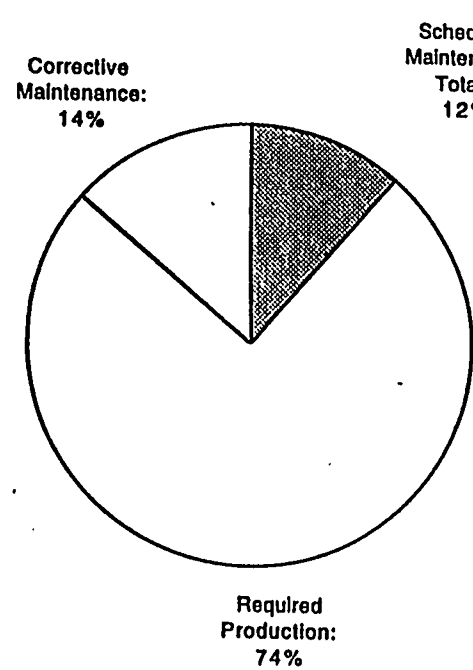
SCHEDULED MAINTENANCE	TOTAL HOURS	TOTAL DAYS	YEAR FRACTION
Scheduled Maintenance Total:	1008	42.0	0.1151
Scheduled Operation:	7752	323.0	0.8849
Required Production:	6563	273.5	0.7493
Corrective Maintenance:	1189	49.5	0.1357

INHERENT AVAILABILITY:

		REQUIREMENTS	ALLOCATION
NC Accelerator		0.9100	0.8297
Target/Blanket		0.9561	0.9561
Tritium Extraction		1.0000	1.0000
Balance Of Plant		0.9730	0.9730
Reserve	0%	1.0001	1.0000
Total APT Plant		0.8467	0.7719

NC APT PRODUCTION AS ALLOCATED (kg): 2.74

Annual Production & Maintenance Budget

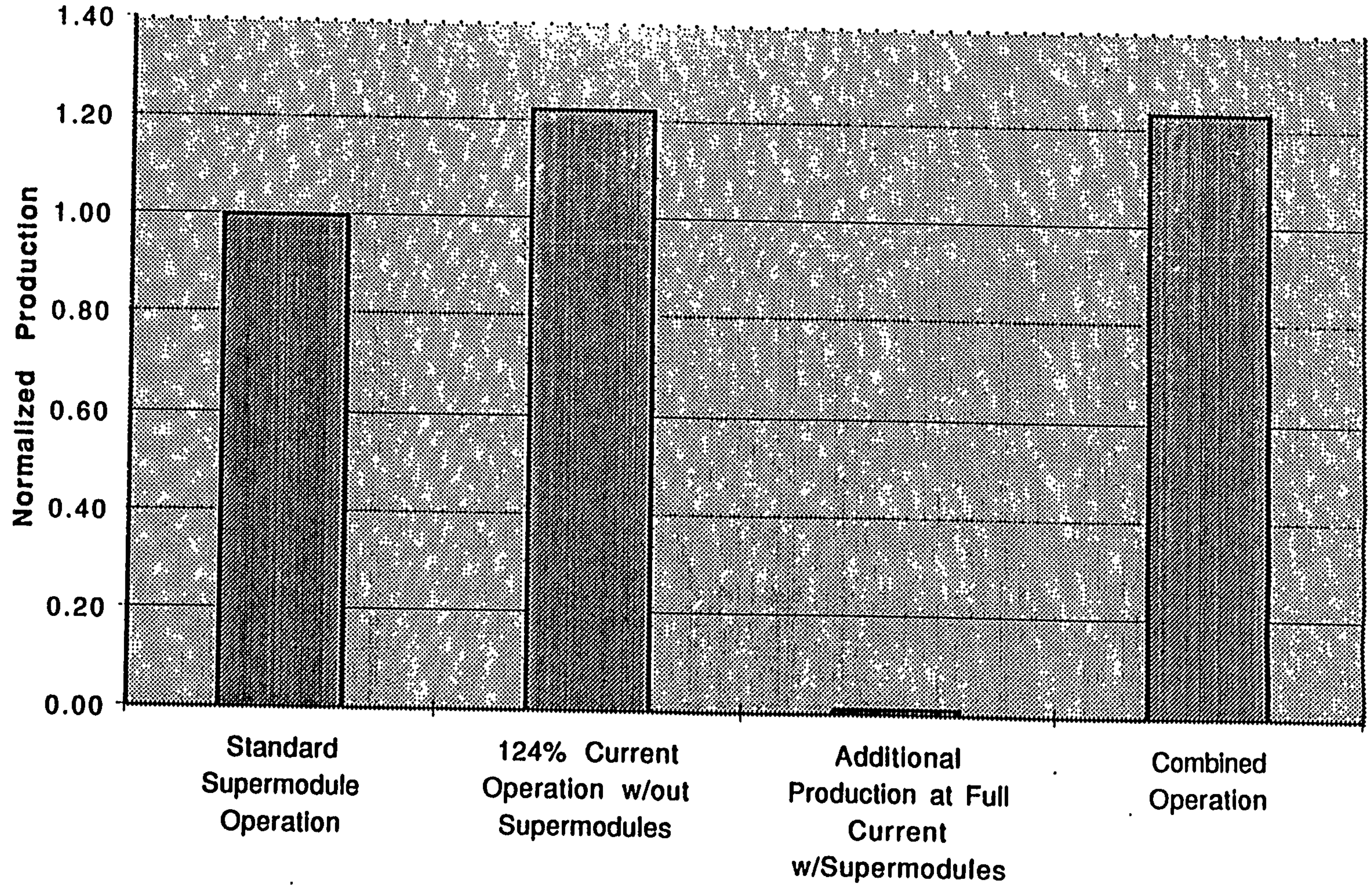


Increased RF Power Operation Improves Performance

In the baseline 100 mA/1780 MeV configuration, the superconducting accelerator operates the RF stations in each supermodule in its normal conducting front end at a reduced capacity so that each supermodule can be treated as a redundant system with one spare. If an RF station in a supermodule is lost, the remaining RF stations pick-up the RF load and the system continues at the same current level of 100 mA as before.

There exists an alternative way of operating the system however. If instead of operating the RF stations at a reduced capacity, they are operated at full power, the accelerator is capable of accelerating higher value of current. This value is limited by the supermodule with the largest number of stations. Hence, the maximum value of current that can be accelerated is 124 mA. This system, however, does not have any additional redundancy in its normal conducting front end. It is possible, though, to continue operation at lower current determined by the RF power capabilities of the supermodule with one failed RF station, eg back at 100 mA. The combined operation buys back about 23 % of the production over a year as shown in the next page.

Increased RF Power Operation Improves Performance



4.0 RF Linac System Trade Studies

The Task 2 effort involved the conduct of system level trade studies involving the cost, RAM, or both aspects of the APT accelerator and plant. These trade studies fall into several categories:

- Sensitivities to design and/or financial uncertainties
- Consideration of alternative operational strategies
- Consideration of more advanced technology alternatives
- Cost/RAMI incentives for potential design refinements
- Evaluation of alternative tritium production growth strategies
- Establishment of RAMI requirements

The results of these system-level trades are summarized in this section. Each of these trades has been conducted at the ~2 or ~3 kg/yr production levels (as noted in the following descriptions), but the general conclusions are independent of the production level. Although only the accelerator parameters are traded, to provide a more complete perspective, the capital, operating and life cycle costs reflect the overall APT plant (i.e., they also include fixed contributions for the balance of the APT facilities).

4.1 Cost Trades

A list of nine APT linac cost trades performed for the Task 2 activity is provided on the next page. These trades primarily addressed the superconducting linac (SCL) design, although some cost trades for the normal conducting linac (NCL) were also performed.

List Of Cost Trades

No.	Trade Title	Description
1	Marginal Cost Per Unit Of Tritium Production	Evaluate the incremental cost associated with a small increase/descrase in SCL tritium production to determine cost sensitivity per percent production
2*	Sensitivity Of Life Cycle Costs To Cost Of Electricity	Consider variations between 20 and 50 mil/kWeH for SCL and NCL designs at ~2 and ~3 kg/yr production levels.
3*	Initial Current/Energy For Baseline SCL System	For ~2 kg/yr production level SCL, determine if there is a cost incentive for operation at 100 mA @1342 MeV or with 74 mA @ 1780 MeV.
4	Supermodule RF Utilization	For ~2 kg/yr production level SCL and NCL, compare operation of all but one rf station in supermodule (max power per station with idle spare) with operation of all stations (lower power per station with operating spare).
5*	Part Year Operation At ~3 kg/Yr To Produce ~2 kg/yr	For ~2 kg/yr production using SCL, consider possible incentives for operation at ~3 kg/yr rate for 2/3 of the time.
6	Revisited SCL Baseline With LANL-Supplied RF Data	This trade reflects late changes to the SCL baseline which incorporate LANL-supplied data.
7*	IOT Vs Klystron	Quantify the advantages for use of advanced IOT rf amplifier tubes in SCL baseline.
8	Cost Incentives For Reduced Aperture	Quantify the cost savings associated with the possibility of reducing the beam aperture in the SCL.
9*	Alternative Growth Strategies	Compare baseline SCL system (initially capable of ~3 kg/yr production) with three alternatives: 1. Initial ~2 kg/yr configuration (1300 MeV, 140 kW per rf drive) configured such that rf tubes are fully utilized (840 kW to rf cavities). Upgradable to final ~3 kg/yr configuration (1700 MeV) by increasing rf drive power to 210 kW and adding RF stations (same as baseline) 2. A 140 kW per rf window/drive line initial/final configuration. (longer than baseline when ~3 kg/yr) 3. A 210 kW per rf window/drive line initial/final configuration (shorter than baseline when ~2 kg/yr)

* Included in DRAFT CDR Section 3

Cost Trade #1: Marginal Cost Per Unit Of Tritium Production

(~ 3 kg/yr Production Level)

The results of a study to determine the "marginal cost of tritium production", defined as the cost to change the production capability by a small amount about the nominal capability, are shown on the next chart. Both the marginal capital cost and the marginal life cycle cost for the linac (only) were calculated. The marginal life cycle cost is relevant to an increase or decrease in the tritium requirement while the marginal capital cost can also be relevant to a situation in which it is desirable to build-in additional reserve (e.g., as a hedge against lower than expected system availability) while not necessarily expecting to produce a different (higher or lower) quantity of tritium.

The approach was to consider an additional cryomodule (and the associated costs incl. rf power, support services, building/tunnel extension) to produce an additional 16.8 MeV of energy and an additional 0.033 kg/yr of tritium (1.05%). The marginal linac capital cost ratio, defined as the capital cost per unit of tritium production at the margin divided by the average capital cost per unit of tritium production, was estimated to be 46%. The marginal linac life cycle cost ratio, similarly defined, was estimated to be 54%. Although the corresponding quantities have not been estimated for the overall APT plant, the expectation is that both ratios will decrease significantly because much of the the balance of facility (target/blanket and balance of plant) cost is independent of small changes in the linac.

These results indicate that increases in production about the current SCL design point can be highly cost effective, but that the benefit for producing less tritium with this design is diminished by the same ratio.

Marginal Cost Per Unit Of Tritium Production

(~ 3 kg/yr Production Level)

Trade Study Objective:

- Evaluate cost of small increase in linac energy and breeding rate

Major Considerations:

- Consider addition of one high β cryomodule, two rf stations and other costs for additional 16.8 MeV
- Calculate added linac capital and life cycle cost, added tritium breeding capability

Conclusions:

- Marginal linac capital cost ratio is 46%of average cost per unit production.
- Marginal linac life cycle cost ratio is 54% of average.
- Most of T/B and BOP cost is fixed, so expect overall plant to have lower (than above) cost sensitivity to tritium production level

Baseline Final Energy	1780 MeV
Energy Increment	16.8 MeV
Baseline T Prod. (@ 75%)	3.15 kg/yr
Tritium Prod. Increment	.033 kg/yr (1.05%)
Baseline Linac Capital Cost	1182 $M
Linac Capital Cost Increment	5.7 $M
Marginal Linac Capital Cost Ratio	5.4 $M/% T Prod.
Baseline Linac Life Cycle Cost	4616 $M
Linac Life Cycle Cost Increment	26 $M
Marginal Linac Life Cycle Cost Ratio	25 $M/% T Prod.

Cost Trade #2: Life Cycle Cost Versus Electricity Cost

The following chart summarizes the impact of the cost of electricity during the first year of operation on the life cycle cost (LCC) of APT plants based upon the normal and superconducting linacs at both production levels, assuming an average plant capacity factor of 75%. [Referring to earlier discussion, the reader is reminded that our LCC definition assumes that the cost of electricity will escalate by 3.8%/yr over the lifetime of the plant and that the discounted value of the electricity charge averages 51% of the first year charge.]

Comparing the values at the high end of the scale (50 mil/kWeH) to those at the low end of the scale (20 mil/kWeH), the LCC sensitivity to the cost of electricity is between 1.8 and 2.4 $B (depending upon which if the four cases) or about 35%. As the baseline value, 34.5 mil/kWeH is somewhat arbitrary and subject to change as the local and national electric power industries evolve, this input should be reevaluated on a regular basis. Opportunities to benefit from off-peak rates should also be considered.

Life Cycle Cost Versus Electricity Cost

Trade Study Objective:

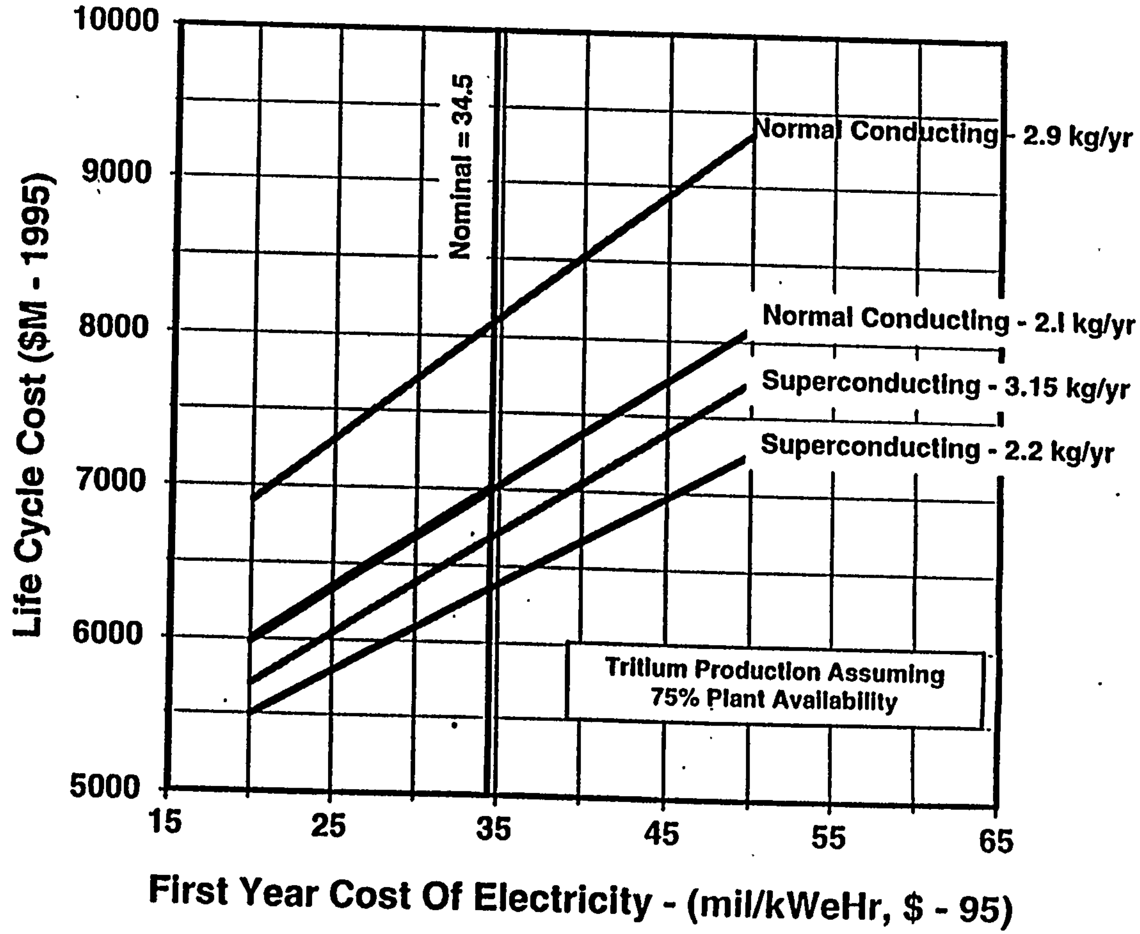
- Understand extent to which total life cycle cost is impacted by electricity cost

Major Considerations:

- Nominal elec. cost = 34.5 mil/kWeHr
- Variations between 20 and 50 mil/kWeHr
- Elec. cost denoted herein is first year cost in 1995 dollars.

Conclusions:

- ~35% LCC sensitivity to uncertainties in indicated range



Cost Trade #3: Initial Current/Energy For SCL System

When the tritium production level is ~2 kg/yr, the operator can chose between high current operation (100 mA) at reduced energy (1340 MeV) or lower current operation (74 mA) at full energy (1780 MeV). The first mode requires dependable operation of the low energy section of the linac (including the ion injector) at its full current and rf power capability, but reduces operational requirements for the rf system (incl. the window/drive line) and electric field level in the high energy section of the SCL. The second mode relaxes the low energy current and rf power requirements, but requires full rf field in the high energy SCL. It also requires a 11% higher window/coupler power level.

The 74 mA current requirement for 1780 MeV operation was determined by recognizing that operation at 1780 MeV, compared with 1340 MeV, results in an ~36% higher spallation neutron yield. Therefore, to produce the same level of tritium as operation at 100 mA, 1340 MeV, a modified current level of 100/1.36 = 74 mA will be required. The resulting tritium production, assuming a nominal plant availability of 75% will be 2.2 kg/yr.

The results indicate a near zero advantage for operation at the higher energy level. [A later study (#5) indicated a much larger advantage if the linac were to be operated at full current and full energy, but over a reduced operating period, to produce ~2kg/yr.]

Initial Current/Energy For SCL System

Trade Study Objective:

- At ~2 kg/yr tritium production levels, compare lifecycle costs for baseline initial operation mode (100 mA, 1340 MeV) with alternative mode (74 mA, 1780 MeV)

Major Considerations:

- Alternative mode requires lower current, but same electric field as ~3 kg/yr operation
- RF coupler power also slightly higher (155 kW vs 140 kW)

Principal Conclusions:

- Operation at 1780 MeV, 74 mA requires ~1.1 MWe less electricity
- Lifecycle cost savings ~$5 M (near zero)
- Operator can chose from a continuous spectrum of operating points

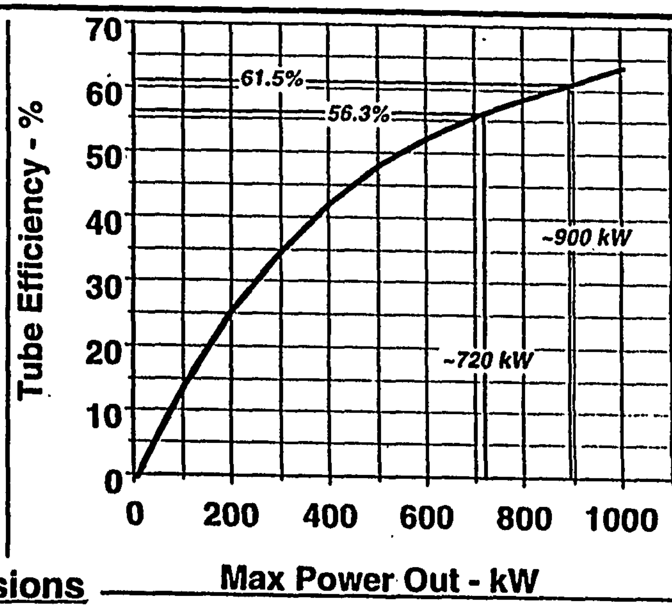
Cost Trade #4: Supermodule RF Utilization (Derating)

Both the NCL and the SCL employ "supermodules" to achieve rf power station redundancy for the normal conducting section of the linac (7-217 MeV for SCL, 7-1300 MeV for NCL). If, during normal operation (all stations operational), all of the stations in a supermodule are used, then the required power from each station is less than if one station is held in standby condition (i.e., not producing power). This operational strategy may lead to longer component lifetime due to component operation at lower than the rated capability , but it also results in lower klystron electrical efficiency.

This study quantifies the annual and life cycle costs of this reduction on effficiency, which can be compared with the projected cost of rf station maintainance, resulting in a goal for station derating. For example, the results indicate that the average rf station component lifetimes in the CCL section of the SCL would have to increase by 37% to justify the loss of efficiency that results from simultanious operation of all of the rf stations. The CCL of the NCL is characterized by a far greater number of larger supermodules. In this case, the benefit for non-simultanious operation is much greater ($129 M vs $29 M).

Supermodule RF Utilization (Derating)

- **Trade Study Objective:**
- Understand if there is a strong economic incentive to operate supermodules most efficiently, such that N-1 klystrons operate at full rated power and 1 spare is in idle standby
- Use above economic incentive to develop a goal for rf component lifetime improvement by power derating
- **Major Considerations:**
- Consider ~2 kg/yr for both normal conducting and superconducting linacs
- For low energy supermodules use of 5:4 stations requires 720:900 kW rf power output
- For high energy, supermodule powers are 771:900 kW
- Klystron efficiencies range from 56.3 - 61.5%



Principal Conclusions

Superconducting Linac (Includes supermodules <217 MeV):

- Use of all N stations, representing a 20% derating compared with use of N-1 stations, requires ~5.3 MWe more electricity ($1.4 M/yr, $ 29 M over life cycle)
- This cost is equivalent to 27% of annual rf power replacement and refurbishment (R&R) budget for the supermodules
- So if rf station lifetimes increase by more than 37%, then should operate all stations

Normal Conducting Linac (Includes supermodules to 1300 MeV):

- Use of all N stations, representing a 16% derating compared with use of N-1 stations, requires ~23 MWe more electricity ($5.9 M/yr, $ 121M over life cycle)
- This cost is equivalent to 20% of annual rf power replacement and refurbishment (R&R) budget for the supermodules
- So if rf station lifetimes increase by by more than 25%, then should operate all stations

Cost Trade #5: Comparison Of Reduced Time Operation At 1780 MeV With Full Time Operation at 1340 MeV To Produce Same Tritium Quantity

The baseline superconducting linac is capable of producing tritium at an instantaneous rate of 4.2 kg/yr (3.15 kg/yr at 75% availability) if it operates at a maximum coupler power of 210 kW to produce a 100 mA, 1780 MeV beam. If the coupler power level is reduced to 140 kW, then the beam energy is reduced to 1340 MeV and the production at 75% plant availability is reduced to about 2.2 kg/yr.

However, if the production requirement is to be lowered to this level, then it <u>may</u> be more economical not to reduce the coupler power and beam energy, but to operate the system at its full capability for a shorter period of time, corresponding to a full power system availability (really a plant capacity factor since the availability will be higher) of 52.4% (= 0.7 x 70%). This question derives from derives from the observation that the tritium production per unit energy at the higher energy (~3.15/1780) is 7.8% higher than the tritium production per unit energy at the lower energy (~2.2/1340). So if the electrical efficiency of the accelerator were the dominant cost component with the other costs fixed, it follows that part time operation at full energy will result in a lower life cycle cost than full time operation (i.e., 75%) at the reduced energy. The analysis shown on the following chart addresses this question.

A review of the scaling of various life cycle cost components is useful for presenting the advantages and disadvantages. The capital cost of the two systems is the same (they are the same accelerator). The annual electricity consumption for "part-time" operation of the sections of the linac through the medium β section, is reduced by 30% because part-time operation requires the same energy and current in these sections, but for 70 % as much time. In comparison, the annual electricity consumption of the high β section is 5% higher than for full time operation at the lower power level (the part time linac operates for 70% as long with 210/140 = 1.5 times as much rf power). However the electric consumption of the high β section is about the same because the klystrons operate more efficiently at full power. The part-time machine requires 30% fewer replacement and refurbishment parts (assuming that the failure rate is not a strong function of the operating power).

Our life cycle cost comparison included all of the above considerations, but ignored others such as the potential for reduced staff (potentially small life cycle cost impact) and the possibility of lower electricity rates for an APT plant that could be operated during off peak periods (a potentially large life cycle cost impact).

The overall result was a decrease in the estimated annual operating cost (relative to full time operation with 140 kW couplers to 1340 MeV) of 32 $M/yr(-17%), resulting in a $653 M (10%) savings in the life cycle cost when the tritium requirement is reduced to 2.2.kg/yr.

Comparison Of Reduced Time Operation At 1780 MeV With Full Time Operation at 1340 MeV To Produce Same Tritium Quantity

Trade Study Objective:

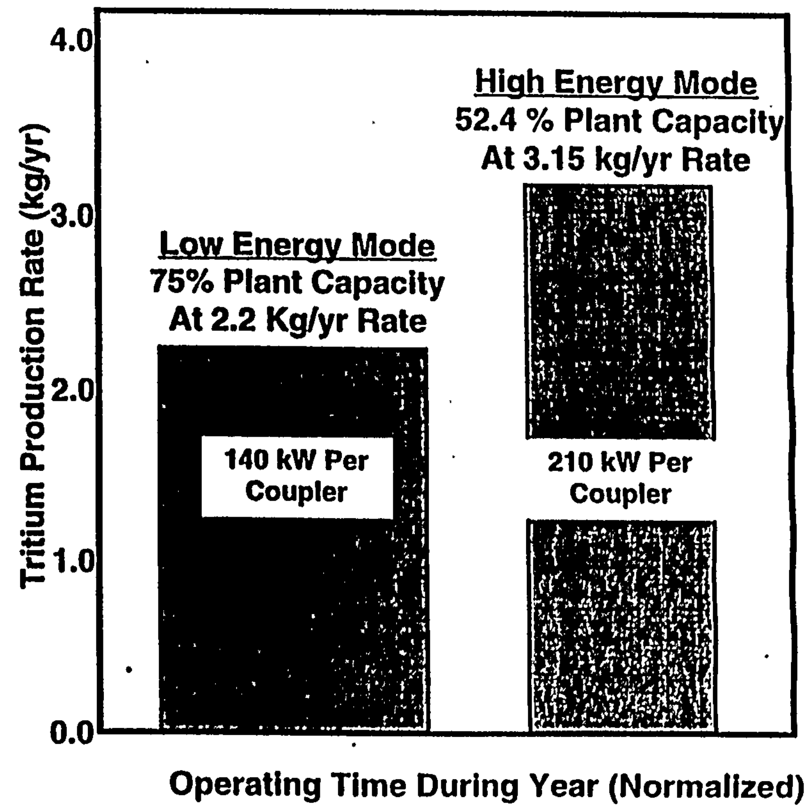
- Consider reduced time operation at 1780 MeV to produce same amount of tritium as full time at 1342 MeV

Major Considerations:

- *Baseline* 2 kg/yr production for 100 mA, 1342 MeV, 75% plant capacity operation includes ~10% margin. *Actual* production is ~2.2 kg/yr
- To produce 2.2 kg/yr with 3.15 kg/yr capability (100 mA, 1780 MeV, 75%) operate for 70% as long (52.4% capacity). Compared with *baseline* :
  - Low energy normal conducting linac and medium β SCL consume 30% less electricity
  - High β SCL consumes about same elec. (3/2 as much rf power, 70% as long, with higher Klystron efficiency)
  - Reduced requirements for replacement parts
  - Potential opportunities for smaller staff, lower elec. rates (not included in analysis)
  - More time for maintenance (lower risk)

Principal Conclusions:

- Operating cost compared with lower rate, full year operation decreases 32 $M/yr (17%)
- Life cycle cost decreases $653 M (10%)



Cost Trade #6: Revisited SCL Baseline With LANL - Supplied RF Data

Updated rf system cost and efficiency data became available from Los Alamos during November, 1996. This data was then incorporated into the ASM model and used for subsequent rf power trades. As shown, the modification in the rf capital cost items off-set one another while the improved efficiency predicted by the newer data leads to a 1.4% savings in the life cycle cost.

Revisited SCL Baseline With Los Alamos - Supplied RF Data

Trade Study Objectives:

- Incorporate Los Alamos-supplied rf cost data and evaluate impact on baseline cost of superconducting linac operating at ~3 kg/yr
- Use revised baseline for subsequent rf power trades

Major Considerations:

- Changes impact cost for: klystron tubes, high voltage power supplies, circulators and loads

Principal Conclusions:

- These changes will result in a 1.4% decrease in the life cycle cost, but will not effect the capital cost
- They will not have a major effect on other conclusions of our study

	Original Model*	Revised Model*
Max. Klystron Elec. Efficiency (%)	64	65
RF Tube And Peripherals Cost ($K each)	200	190
HV Power Supply Cost ($K each)	394	370
Circulator & Load Cost ($K each)	81	116
RF Power Station Cost ($K each)	1450	1451
Accelerator Total Cost ($M)	1192	1193
Plant Total Cost ($M)	2526	2527
Annual O&M Cost ($M)	207	202
Total Life Cycle Cost ($M)	6740	6645

* Data refers to 700 MHz components. All costs refer to average over 237 lot quantity

Cost Trade #7: Advanced IOT vs Klystron

An advanced inductive output tube (IOT) for 1 MW CW operation at 700 MHz is currently under development by CPI under Los Alamos funding. This technology promises some minor capital cost savings, but the real incentive for its development is the promise of higher operating efficiency (24% higher in this analysis). Our results indicate that the use of advanced IOT technology could save the program $17 M/yr in operating costs, equivalent to a discounted life cycle cost savings of $366 M (5.8%).

Advanced IOT vs Klystron

Trade Study Objective:

- Determine the magnitude of the economic advantage for use of advanced power tube technology for super-conducting linac operating at ~3 kg/yr

Major Considerations:

- Compared with 700 MHz mod-anode version of "super-klystron", advanced IOT promises higher efficiency over full power range (class "C" operation), lower voltage operation, lower cost
- Downsides include lower gain (larger driver required), less technological heritage (e.g., no failure rate data)

Principal Conclusions:

- If it lives up to its promise, this tube can save 17 $M/yr O&M (primarily electricity) and reduce life cycle cost by $366 M (5.8%)

	Klystron	IOT
Frequency, MHz	700	700
RF Power, kW	1000	1000
Max. Elec. Efficiency (%)	65	73
Typ. Operational Efficiency (%)	58	72
Voltage (kV)	95	45
Gain (dB)	40	25
Driver Power (kW)	0.1	3.2
Assumed MTBF (hr)	25,000	25,000
Tube & Peripheral Cost ($k)	190	145
HVPS Cost ($k)	370	327
RF Driver Cost ($k)	2	56
Cooling System Cost ($k)	100	86
RF Station Cost	1446*	1413*
Accelerator Cost ($M)	1193	1182
Plant Cost ($M)	2527	2516
Annual O&M Cost ($M/yr)	202	185
Life Cycle Cost	6645	6279

* Data refers to 700 MHz components. All costs refer to average over 237 lot quantity

Cost Trade #8: Cost Incentives For Reduced Aperture

The ratio of the SCL beamline aperture to the beam radius is very large and somewhat arbitrary (a safety factor). Therefore it is of interest to examine if there are strong cost incentives to use a smaller aperture. The results of this study, which consider magnet cost savings resulting from a reduction in the aperture size indicate that this aspect of the cost will not drive the design to a smaller bore.

There are, however, other factors which should be considered. One such factor involves radiation heating into the cryostat, which will be reduced if the aperture is decreased. Another involves the required separation between the superconducting rf cavities and the singlet magnets, which is also decreased as a function of the aperture size, resulting in a shorter linac and savings in the cost of the tunnel. The later consideration may become the most important, but it is not expected to be a strong cost driver.

Cost Incentives For Reduced Aperture

<u>Trade Study Objective</u>:

- Understand financial incentives for reducing beam aperture in superconducting linac if consideration of beam loss and consequent activation allows a reduction

<u>Major Considerations</u>:

- Consider reduction in aperture clear bore from 5 inches (nominal) to 1 inch
- Cost impact on rf cavities and cryostat will be minimal
- Cost of 519 superconducting EMQs in 108 SCL cryostats will decrease
- Scale magnet costs with bore size in range of 1 - 5 in. while holding field gradient constant

<u>Principal Conclusions</u>:

- Saving (about $2.5 M for decrease to 3 inches) probably not large enough to justify losing risk reduction benefit of oversize bore
- If include HEBT EMQs in analysis, benefit will increase, but expect overall conclusion to be the same

Magnet Bore (in)	Magnet Bore (cm)	Magnet Material Cost ($K)	Magnet Labor Cost ($K)	Total Cost Per Magnet ($K)	Total Cost For 519 Magnets ($M)
5	12.7	4.9	11.5	16.4	8.5
4	10.2	3.5	10.5	14.0	7.3
3	7.6	2.3	9.3	11.6	6.0
2	5.1	1.2	7.9	9.2	4.8
1	2.5	0.4	6.0	6.5	3.4

Trade #9: Alternative Growth Strategies (con't)

and the 2:1 splitters are replace with existing and new 1:1 splitters. In this scenario, the above-mentioned splitters are located away form the linac in the rf hall (which is initially sized for the upgraded rf level), so that the transfer can be affected without disturbing the accelerator hall (except perhaps to install more capable rf couplers). This case and Case A both assume that the rf coupler will be tunable to match the rf system to the accelerating cavities over the 140 - 210 kW coupler power range.

Strategy D starts with the same, more efficient configuration as strategy C, but assumes that the coupler power will not be allowed to grow, but will be fixed at 140 kW. Therefore, to produce 3.15 kg/yr, the linac structure must be lengthened and the additional 52 rf stations must be provided along side. The longer rf hall and tunnel that will ultimately be added and the increased HEBT cost to traverse it prior to the upgrade are included in the initial cost.

Strategy E assumes that the coupler power can be fixed at 210 kW from the outset. Therefore, the initial configuration is shorter (and uses the same amount of installed power as Strategies C and D). To produce 3.15 kg/yr, the linac structure must be lengthened and the additional 52 rf stations must be provided along side (at which time it becomes identical to the baseline). The longer tunnel, rf hall, and the increased HEBT cost to traverse it prior to the upgrade are, again, included in the initial cost.

Alternative Growth Strategies
(Depending Upon Achievable RF Coupler Power)

Initial 2.2 kg/yr

	E	A, B, C, D	
Superconducting Sections	664 m	996 m	1392 m
		A, B, C, E	D

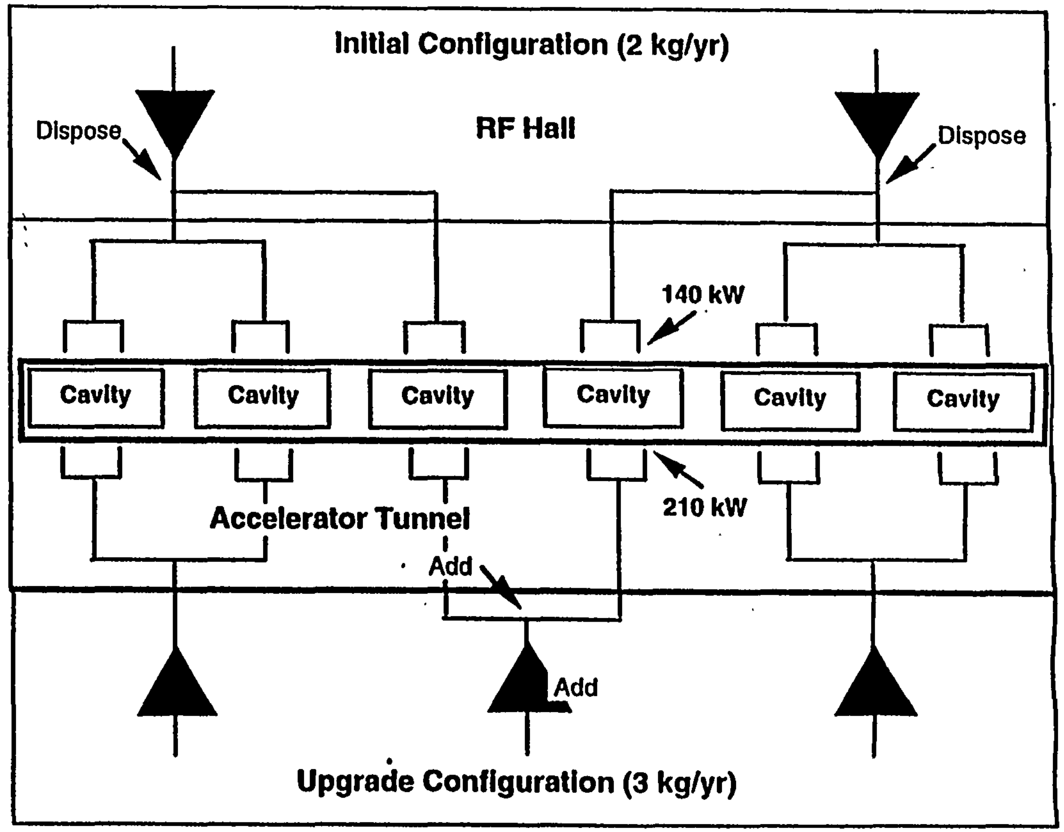
Growth 3.15 kg/yr

Strategy	Description	Initial 2.2 kg/yr			Growth 3.15 kg/yr		
		SCL Lgth.	RF Power/Coupler	No. RF Sta.*	SCL Lgth.	RF Power/Coupler	No. RF Sta.
A	Baseline	996	140	237	996	210	237
			Increase Coupler Power →				
B	Baseline With Reduced Operation Time** @ 3.15 kg/yr	996	210	237	996	210	237
			Operate Full Time →				
C	Lower Initial Installed RF Power	996	140	185	996	210	237
			Add RF Stations & Increase Coupler Power →				
D	Low Coupler Power Limit	996	140	185	1392	140	237
			Add Cryomodules & RF Stations →				
E	High Coupler Power Limit	664	210	185	996	210	237
			Add Cryomodules & RF Stations →				

* This is the number of rf stations in the 52.4% plant capacity factor compared with nominal 75%

Growth Strategies: Path C, RF Reconfiguration

- Each RF station initially serves three cavities, each driven by two 140 kW couplers (840 kW total)
- In upgrade configuration, each original tube serves two cavities, corresponding to two 210 kW couplers (840 kW total).
- When the switchover is made, two center cavities of every six cavities require new 840 kW RF station
- Six cavities per cryomodule shown, but smaller cryomodules may also be possible



Growth Strategies: Path C, Design & Cost Implications

- Most rf transport lines and other components can be preserved, with very few exceptions. Equipment changes for each six cavities:

  - Remove two 1:2 splitters
  - Add one 1:1 splitter
  - Add one rf power station

- To upgrade from 1300 to 1700 MeV will need to repeat this 48 times

  - Add 40/0.84 = 48 new RF stations
  - Add 48 new 1:1 splitters
  - Discard 96 old 1:2 splitters

- Changeover could be relatively quickly and cost impact minimized if initially build full size rf hall anticipating upgrade and if all high power splitters are located outside the accelerator tunnel, in the rf power hall.

  - Additional waveguide required

Growth Strategies: Paths D & E, Hi & Low Power Coupler Limits

Path D: Limited To 140 kW Coupler

Initial (~2 kg/yr)	Growth (~3 kg/yr)

1340 MeV, 996 m SCL — 1780 MeV. 1392 m SCL

Changes:

- Initial buy can delete 52 rf stations ($68 M) and their R&R cost and elec. inefficiency costs, but must add 396 m extra tunnel ($33 M) and extra HEBT section($6 M)
- Final buy must include 39 additional cryomodules ($44 M) and additional rf transport components ($6M)

Path E: Early Validation Of 210 kW Coupler

Initial (~2 kg/yr)	Growth (~3 kg/yr)

1300 MeV, 664 m SCL — 1700 MeV, 996 m SCL

Changes:

- Initial buy can delete 33 cryomodules ($39 M), 52 rf stations and their R&R cost , but add extra 332 m HEBT section ($5 M)

Alternative Growth Strategies: Results

The estimated capital and life-cycle costs for the five alternative operating strategies discussed on the previous pages are summarized and compared in the next two charts. In each case, the initial capital costs include allowances for facilitating system growth (e.g., the initial cost for Case D includes a long enough tunnel to accommodate the longer accelerator that will be required for growth from 2.2 kg/yr to 3.15 kg/yr). However there is no assumption on how long the system might operate at the lower production level (i.e., the life cycle cost is based upon 40 years operation at the specified level).

As shown, the lowest life cycle cost, a 10% improvement, is provided by Case B (part-time operation at full capability). As noted earlier, the tritium production efficiency is about 8% higher at the higher energy. This advantage, combined with improved rf system efficiency at full power, drives the result.

Case C (lower installed rf power) results in a 2.9% lower capital cost and a 5% lower life cycle cost than the baseline (Case A) operated full time at the lower production level. The majority of the advantage results from more efficient operation.

Case D (140 kW coupler limit) is more expensive than Case C because the initial configuration requires a longer tunnel, a HEBT to conduct the beam over the tunnel

(Continued Next Page)

Alternative Growth Strategies: Results (con't)

and, ultimately, a longer linac structure. It still provides some advantage at the lower production level. The cost penalty at the higher level is small, 4% of the capital cost and 1.6% of the life cycle cost.

Case E (210 kW couplers) provides the lowest capital cost at the lower production level, but the benefit is still less than 5% of the overall capital cost of the plant. The life cycle cost reduction is comparable to that of Cases C and D, about half of the savings that can be obtained from Case B.

With the exception of Case D (4% higher), the capital and life cycle costs after system growth to the 3.15 kg/yr level are nearly the same. This result is somewhat optimistic because the estimates do not the inevitable costs associated with a construction program disruption, which could be substantial.

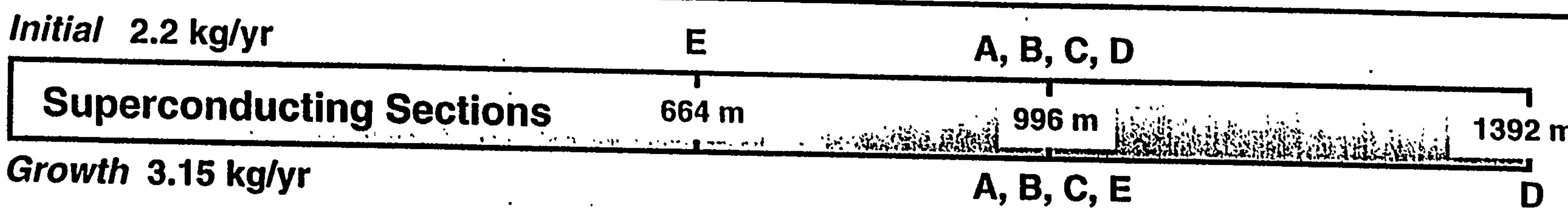
In summary, there appears to be little incentive to move from the baseline. It provides the lowest life cycle cost at the lower production level without a substantial cost penalty. However, if the risk associated with the 210 kW coupler is high, the financial penalty for the 140 kW coupler power is small and quite manageable within the overall context of the APT life cycle cost.

Alternative Growth Strategies: Results

	Strategy A (Baseline)		Strategy B (Part Time Operation)	Strategy C (RF Reconfig.)		Strategy D (140 kW Couplers)		Strategy E (210 kW Couplers)	
	Full Time @2.2 kg/yr	Full Time @3.15 kg/yr	Part Time @3.15 kg/yr	Initial Config.	Final Config.	Initial Config.	Final Config.	Initial Config	Final Config
Annual Tritium Breeding (kg/yr)	2.2	3.15	2.2	2.2	3.15	2.2	3.15	2.2	3.15
Plant Capacity Factor (%)	75	75	52.5	75	75	75	75	75	75
Final SCL Energy (MeV)	1340	1780	1780	1340	1780	1340	1780	1340	1780
Length Of SCL Sect. (m)	996	996	996	996	996	996	1392	664	996
Assoc. Tunnel Length (m)	996	996	996	996	996	1392	1392	996	996
Number Of Installed RF Stations	237	237	237	185	237	185	237	185	237
Plant Capital Cost ($M)	2526	2526	2526	2453	2531	2499	2634	2413	2532
Change From Baseline Capital Cost ($M)	NA	NA	NA	-73	+5	-27	+108	-113	+6
Change From Baseline Capital Cost (%)	NA	NA	NA	-2.9	+0.4	-1.3	+4.0	-4.5	+0.2
Annual O&M Cost ($M/yr)	192	207	160	179.5	207.0	179.9	208.0	179.1	207.0
Life Cycle Cost ($M)	6443	6749	5790	6114	6754	6170	6877	6065	6754
Change From Baseline LCC ($M)	NA	NA	-653	-329	+5	-273	+128	-378	+5
Change From Baseline LCC (%)	NA	NA	-10	-5.0	+0.2	-4.4	+1.6	-5.6	+0.1

Analysis does not include cost increases due to program interuption

Summary Of Comparative Capital & Life Cycle Costs For Alternative Growth Strategies



Strategy	Description	Initial 2.2 kg/yr		Growth 3.15 kg/yr	
		Plant Capital Cost ($M)	Plant Life Cycle Cost ($M)	Plant Capital Cost ($M)	Plant Life Cycle Cost ($M)
A	Baseline	2526	6448	2526	6740
B	Baseline With Reduced Operation Time* @ 3.15 kg/yr	Same	-10%	Same	Same
C	Lower Initial Installed RF Power	-2.9%	-5.0%	+0.4%	+0.2%
D	Low Coupler Power Limit	-1.3%	-4.4%	+4.0%	+1.6%
E	High Coupler Power Limit	-4.5%	-5.6%	+0.2%	+0.1%

* 52.4% plant capacity factor compared with nominal 75%

4.1 RAMI Trades

A list of seven APT linac RAMI trades performed for the Task 2 activity is provided on the next page. These trades primarily addressed the superconducting linac (SCL) design, although some RAMI trades for the normal conducting linac (NCL) were also performed.

List Of System Trade Studies (Primarily RAMI Trades)

No.	Trade Title	Description
10	RAMI Sensitivities To Data Uncertainties	Consider sensitivities of key availability drivers to uncertainties in RAMI data (e.g., failure rates, repair/replace times). Consider normal and superconducting systems.
11	Required Levels Of Redundant Cryomodules and RF Power Stations	Determine the required levels of "operate through" redundancies in the superconducting linac.
12	Ion Injector Spares	Consider possibilities for availability improvement by use of one or more spare ion injectors.
13	Clam Shell EMQ's In HEBT	Consider possibilities for availability improvement by use of "clam shell" EMQ configurations in HEBT that do not require vacuum break for repair or replacement.
14A & 14B	Optimal Operating Mode For Supermodules	Consider the increased beam current level that can be supported in the 2 kg/yr normal conducting linac (#15A) and the 3 kg/yr superconducting linac (#15B) if the maximum amount of rf power capacity in the supermodules were to be used. [Assume that this increased beam current can be produced by the ion injector and transported through balance of the linac.] Assume that machine will operate at this increased level unless an rf station is out of service. If so, then the production level will be decreased to the nominal level (2 kg/yr for the NC case and 3 kg/yr for the SC case) while the rf station is repaired. Calculate the effective level of tritium production and compare with the nominal level.

Trade #10: RAMI Sensitivities To Data Uncertainties

Trade Study Objective:

- Recognizing that there are uncertainties in the RAMI data base, determine which uncertainties have the greatest effect on the overall accelerator system availability

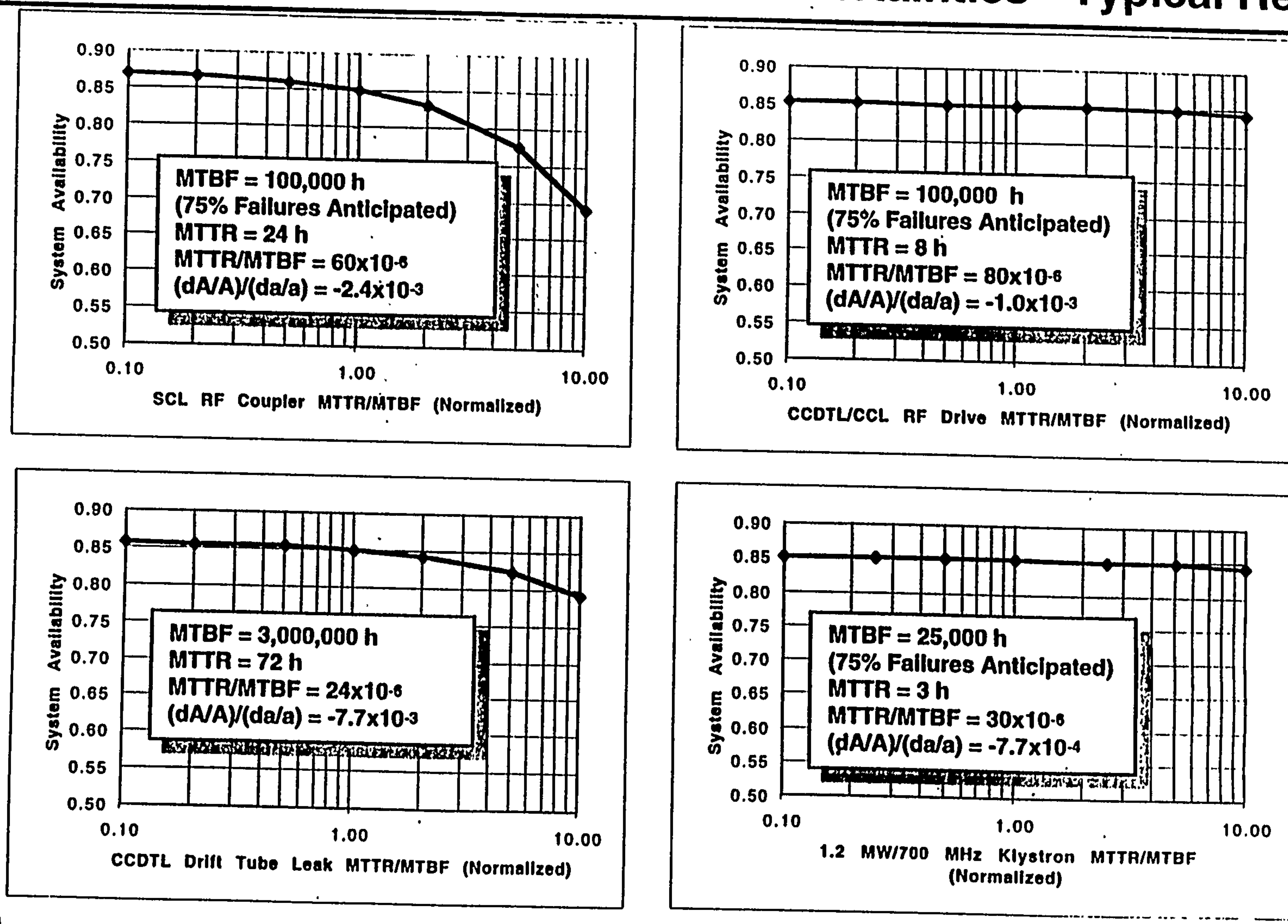
Major Considerations:

- Consider uncertainties in MTBF (failure rate) and MTTR (repair time)
- System availability is a function of a dimensionless parameter, α = MTTR/MTBF.
- Availability sensitivity can be represented in a dimensionless form: $S = (dA/A) / (d\alpha / \alpha)$, where A is accelerator system availability.

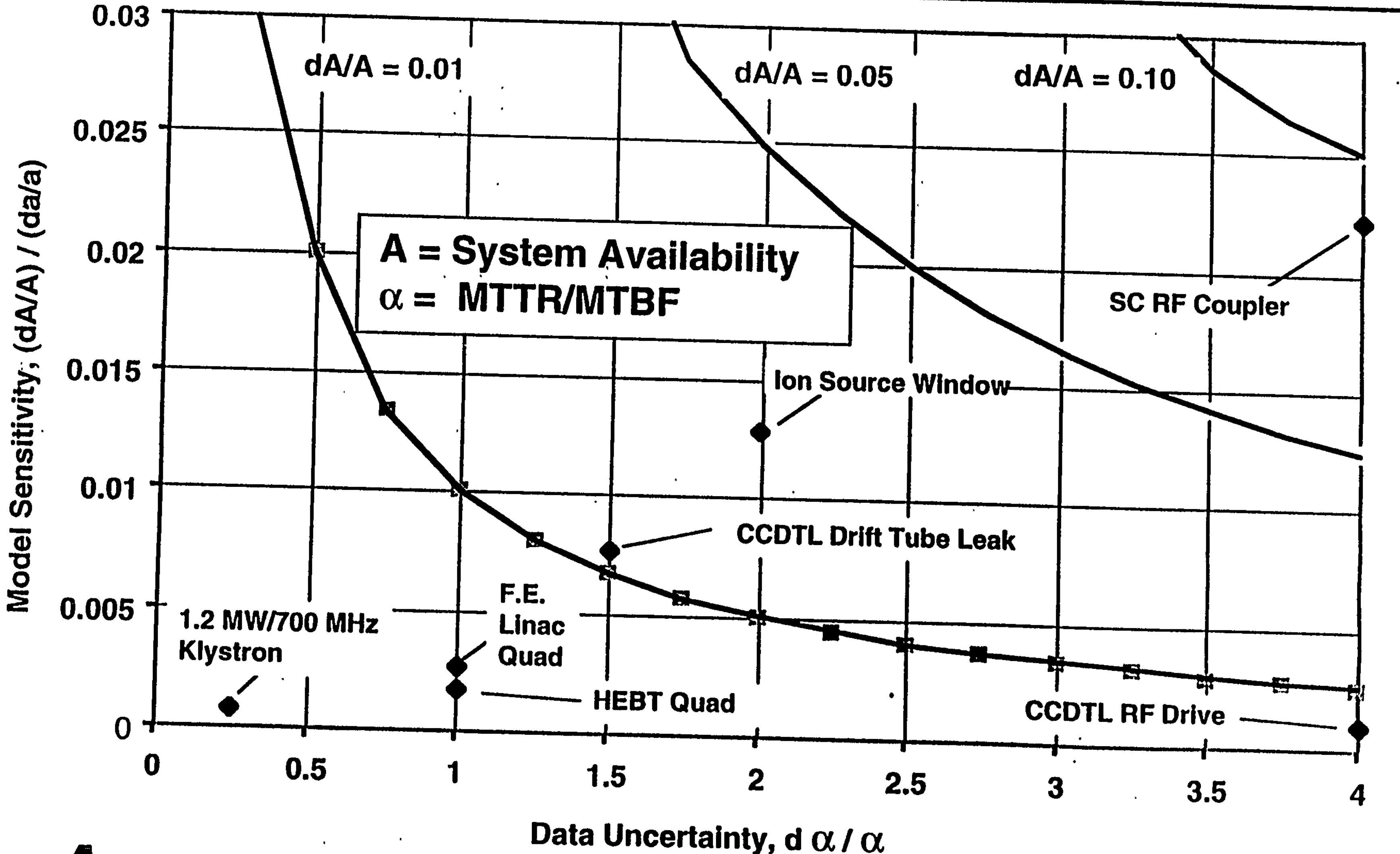
Principal Conclusions:

- The SCL rf coupler/window is a strong driver of system availability with a large uncertainty associated with its failure rate. Although undesirable, such a loss of availability would be tolerable and could be offset by additional performance elsewhere in the system(see Section 2.0).
- Ion source window is another important element with high sensitivity and relatively large uncertainty. High system availability sensitivity to the ion source window is driven by the low MTBF value of this item. Design for maintainability and continuing reliability improvement are crucial for this item.

Trade #10: RAMI Sensitivities To Data Uncertainties - Typical Results



Trade #10: RAMI Sensitivities To Data Uncertainties - Importance Plot



Trade #11: Required Levels Of Redundant Cryomodules and RF Power Stations

Trade Study Objective:

- A key question of interest to the designers of the SCL is the number of required cryomodule spares which is necessary to obtain the required availability level. An analysis was performed to investigate this issue.

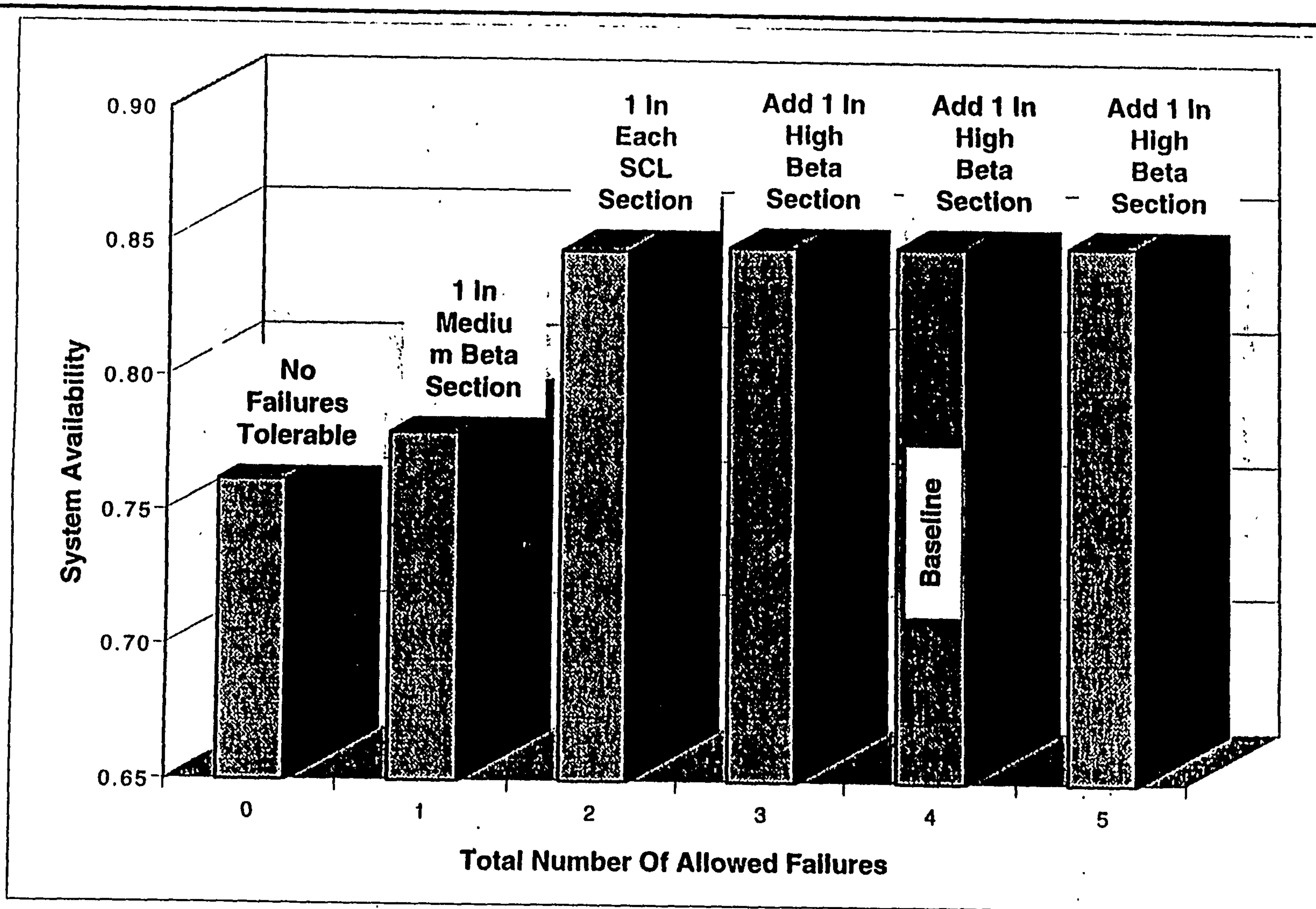
Major Considerations:

- The baseline SCL includes five in-line spare cryomodules
- If an individual failed cryomodule or component thereof fails, the remaining modules can be rephased to continue operation with little loss in performance
- However, there is likely to be a constraint on the concurrent failure of adjacent or near-adjacent cryomodules (Beam Dynamics Analysis Required)
- Also, if rf power station fails it can be repaired on-line. If the cryomodule or rf coupler fails, must wait for accelerator to be down before repair will be possible

Principal Conclusions:

- Spare cryomodules must be distributed over both medium and high beta sections of SCL
- No fewer than two spares (one in each section) should be allowed.

Trade #11: Required Levels Of Cryomodule Redundancy - Results Of Analysis



Trade #12: Ion Injector Spares

Trade Study Objective:

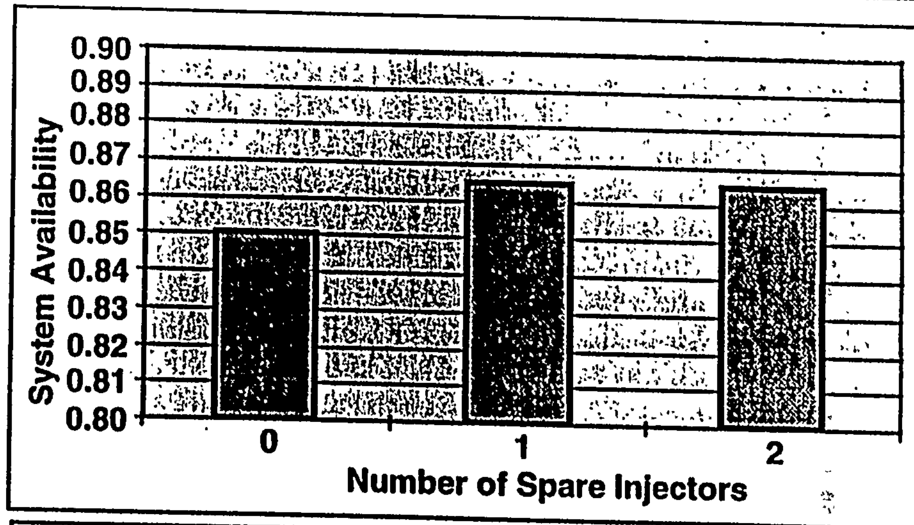
- Determine the availability and reliability benefits for one or more spare ion injectors

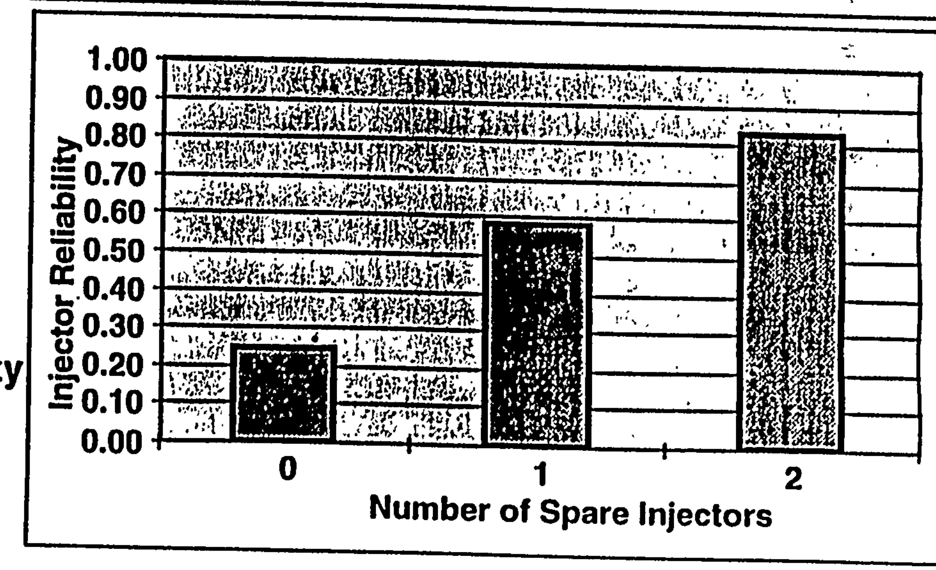
Major Considerations:

- Ion injector has short MTBF
- Therefore it is an availability and reliability driver
- Its low cost suggests that redundancy should be explored
- However, there may be technical issues:
    - Additional components in tandem configuration
    - Long LEBT (beam quality)

Principal Conclusions:

- Dual injector buys about 1.5% in availability and doubles reliability
- If technically feasible, it should be seriously considered

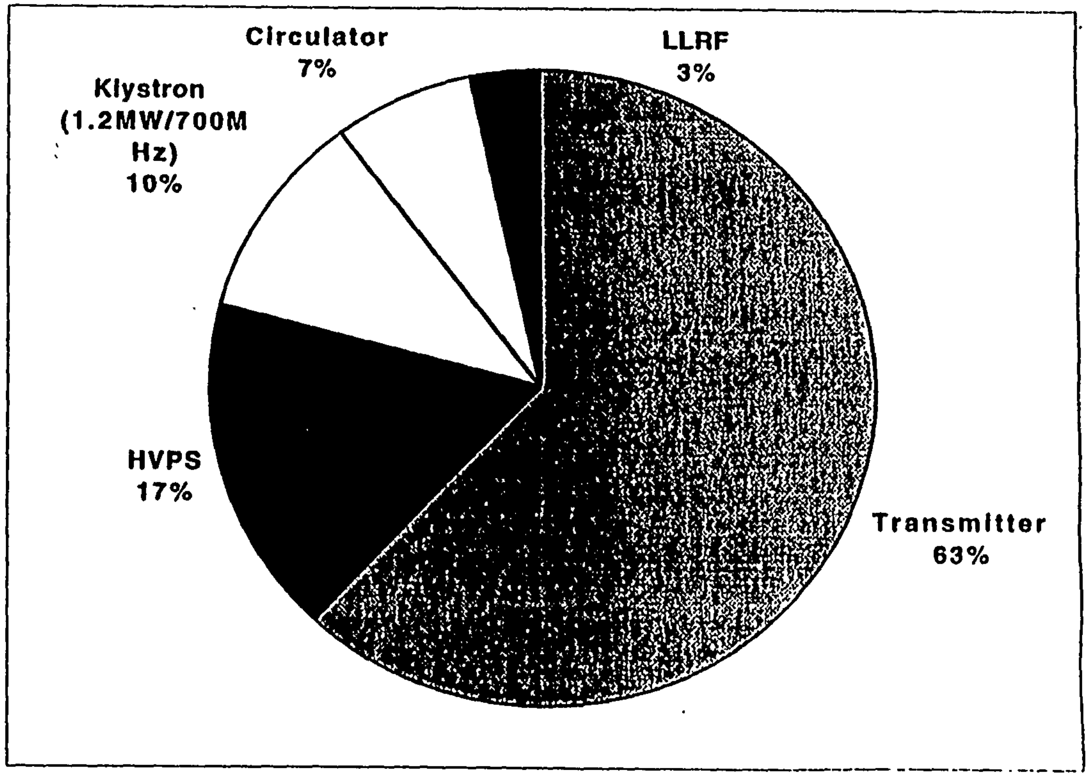




Trade #13: Improved Diagnostics To Avoid Supermodules

Trade Study Objective:

- Consider the potential effectiveness of the diagnostics for prediction of anticipated failures of the klystron in the rf station and a possibility of using highly efficient diagnostics instead of supermodules
- Consider supermodules to 217 MeV in
- superconducting accelerator



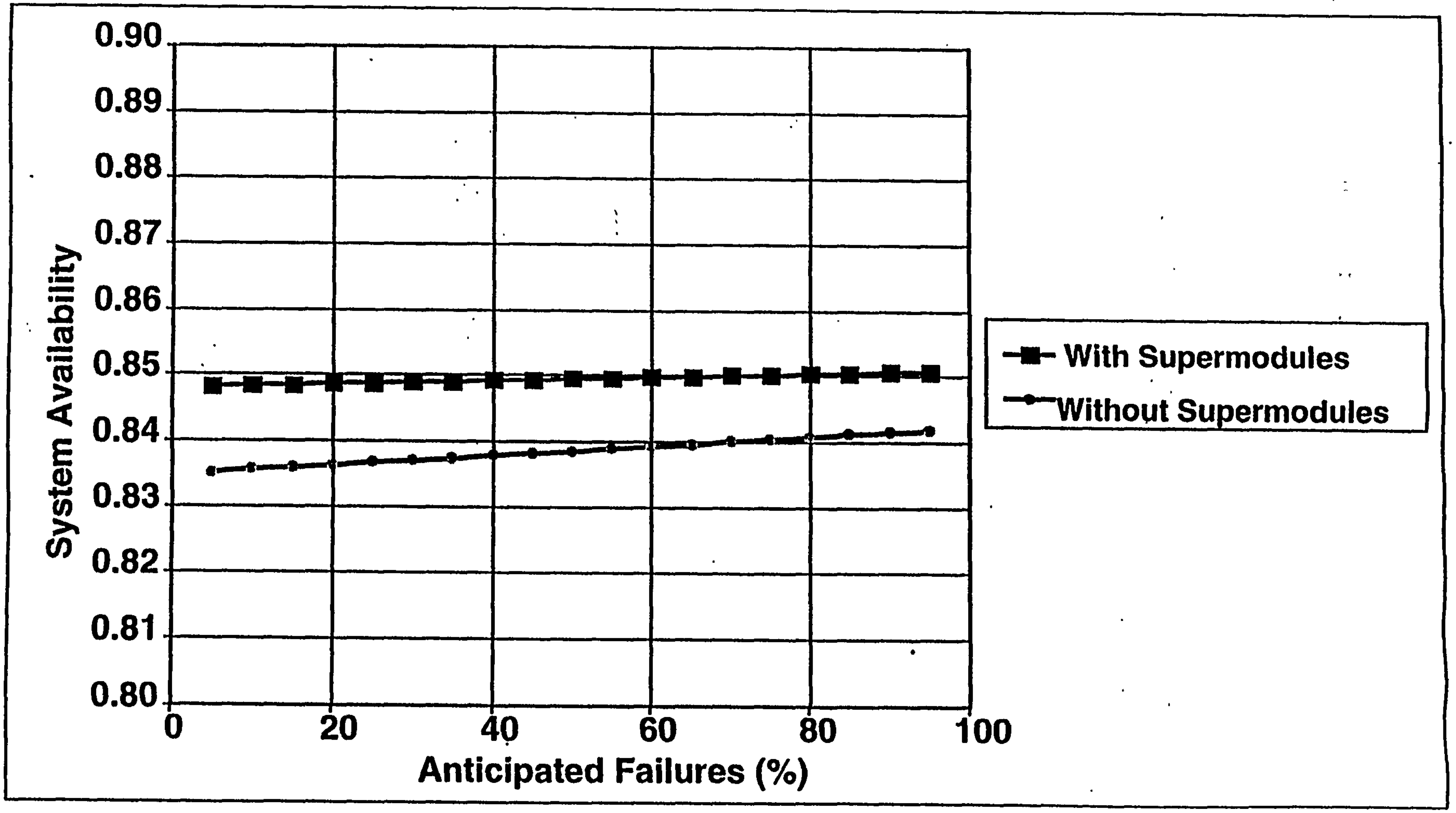
Major Considerations:

- The klystron is only one contributor to the rf station availability budget. HVPS, transmitter electronics also major contributors
- Due to redundancy in supermodules and failure tolerant SCL, the rf station itself has a diminished effect on system availability

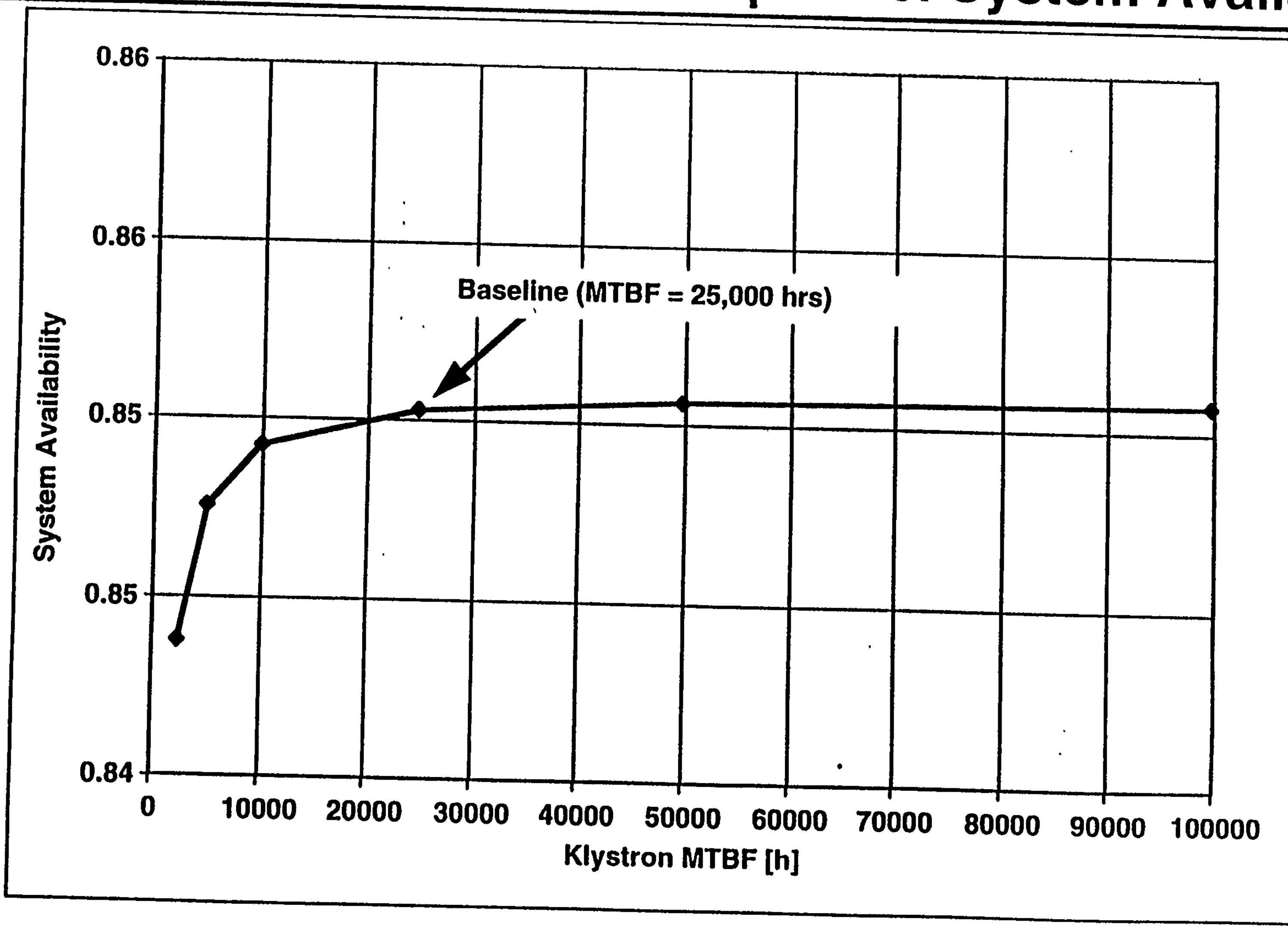
Principal Conclusions:

- Without supermodules the system availability decreases by 2%
- To recover this advantage will have to employ effective diagnostics not just for klystron, but for all major components of rf station
- Same conclusion for normal conducting accelerator

Trade #13: Improved Diagnostics To Avoid Supermodules - Effect of Klystron Failure Diagnostic Efficiency On System Availability



Trade #13: Improved Diagnostics To Avoid Supermodules - Effect of Klystron MTBF on the Top Level System Availability



Trade #14A: Optimal Operating Mode For Supermodules In Normal Conducting Linac

Trade Study Objective:

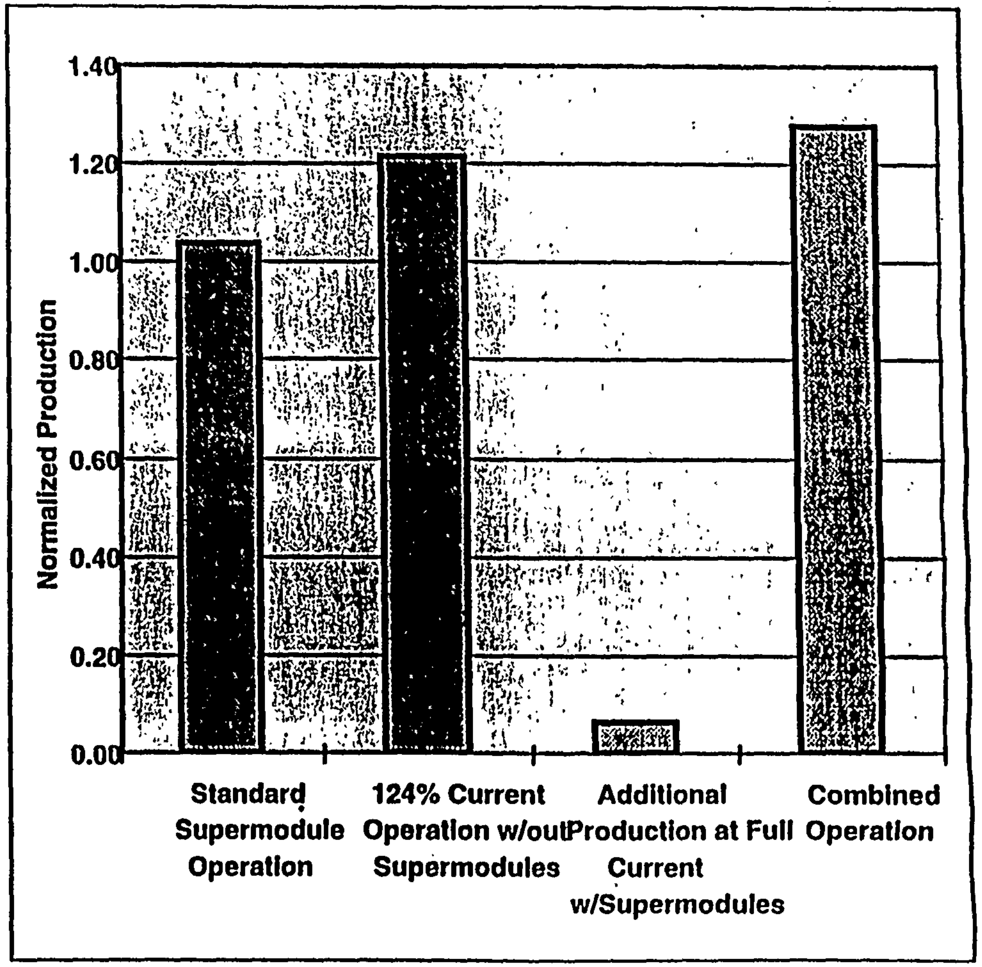
- In the baseline 100 mA/1300 MeV NC Linac, the rf stations operate at reduced capacity. If they are operated at full power, the normal conducting accelerator is capable of accelerating higher value of current. The objective of the present trade study is to determine the potential benefit of such operation.

Major Considerations:

- The maximum value of beam current in the full power operation is limited by the supermodule with the largest number of stations to 124 mA. This system, however, does not have any additional redundancy. It is possible, though, to continue operation at lower current determined by the rf power capabilities of the supermodule with one failed rf station, e.g. back at 100 mA.

Principal Conclusions:

- The combined operation results in additional output of about 28 % of the production quota over a year.



Trade #14B: Optimal Operating Mode For Supermodules In Superconducting Linac

Trade Study Objective:

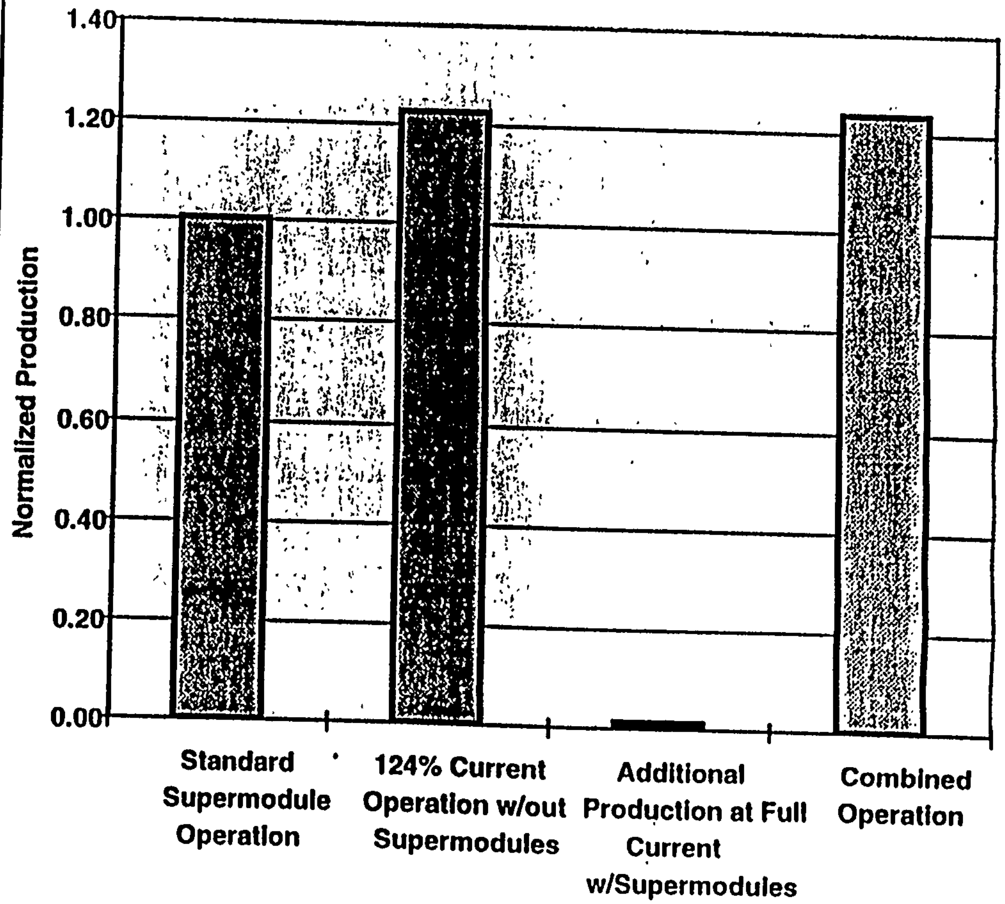
• In the baseline 100 mA/1780 MeV SC Linac, the rf stations operate at reduced capacity. If they are operated at full power, the normal conducting part of this accelerator is capable of accelerating higher value of current. The objective of the present trade study is to determine the potentia benefit of such operation.

Major Considerations:

•The maximum value of beam current in the full power operation is limited by the supermodule with the largest number of stations to 124 mA. This system, however, does not have any additional redundancy in the normal conducting front end. It is possible, though, to continue operation at lower current determined by the rf power capabilities of the supermodule with one failed rf station, e.g. back at 100 mA.

Principal Conclusions:

•The combined operation results in additional output of about 23 % of the production quota over a year.



5.0 Task 3: Manufacturing Schedule Evaluation

After a review of the Los Alamos Conceptual Design as of 6 August 1996, independent APT Fabrication Process Flows and Manufacturing Schedule/Cycle Plans were developed for the Baseline Normal Conducting Accelerator and the Superconducting Accelerator Configuration.

These results are presented in section 5.1 "Accelerator Subsystem Manufacturing Considerations" and Section 5.2 "Evaluations of Integrated Production Schedules".

5.1 Accelerator Subsystem Manufacturing Considerations

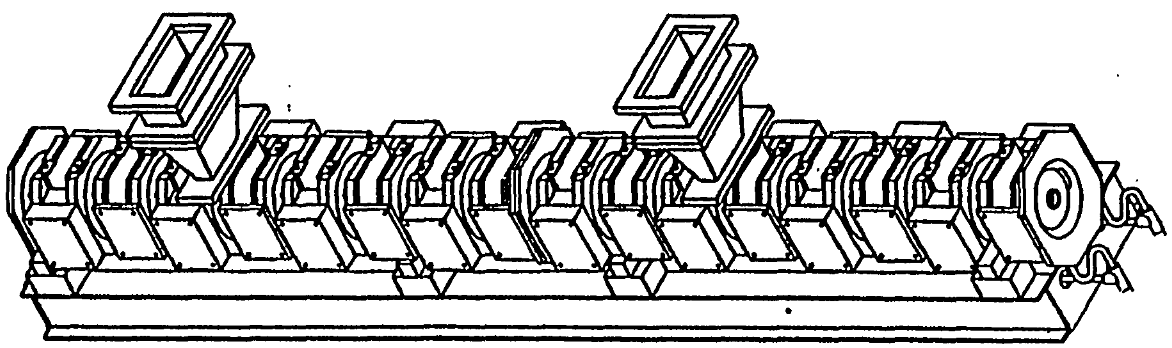
High rate production components that were reviewed included the Coupled Cavity Drift Tube Linac (CCDTL), the Coupled Cavity Linac (CCL), Superconducting Accelerator Structures and Supporting RF Power Stations. Emphasis was placed on gaining an understanding of Critical Path Fabrication Concerns, Final Assembly, integration and test requirements as well as unique factory requirements. Longlead procurements, requirements and potential suppliers were identified.

Possibilities for improvement in areas involving manufacturing producability, cost and quality were reported.

5.1.1 Normal Conducting Accelerator Structures CCDTL

Critical Path Activities for Developing a Detailed Manufacturing Plan

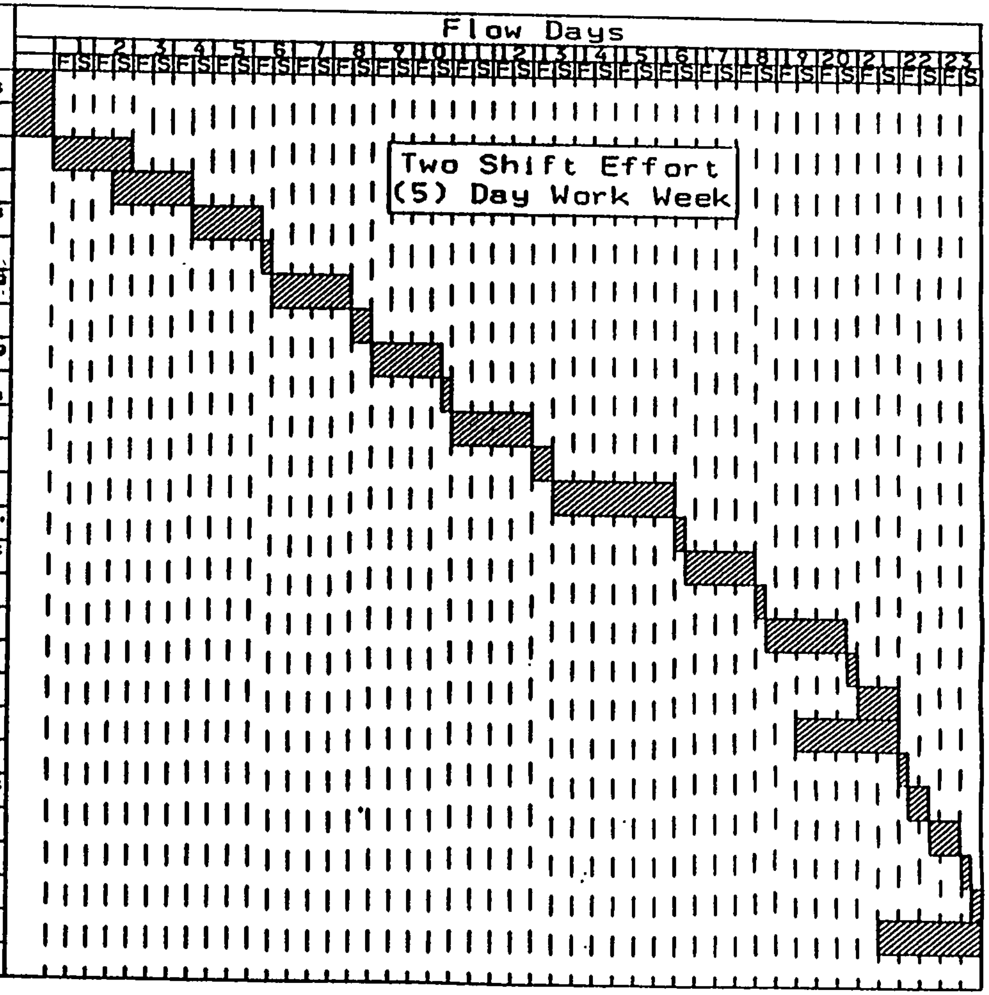
- 3 Braze cycles and 2 anneal heats for flanged section build
- Leak test after each braze operation
- Strict adherence to cleaning, chemical deoxidization and handling procedures
- Tuning steps include performing frequency and coupling measurements during stack tune and flange section tune



APT Room Temperature CCDTL I Flanged Section

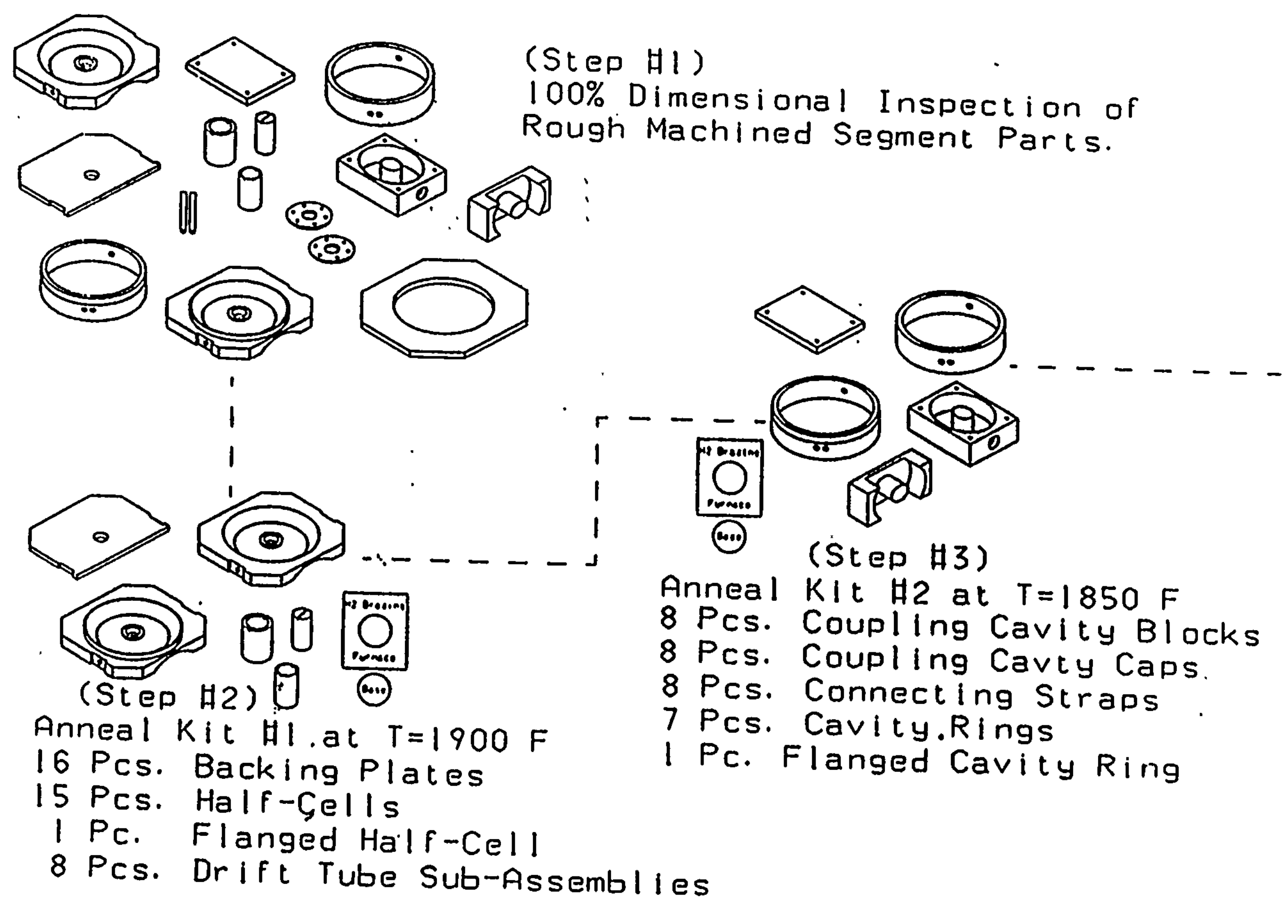
Typical In-House Manufacturing Assembly Flow

ID	Name	
—	Vendor Blister Check and Rough Machine Parts	
1	Inhouse Receiving Inspection 100%	
2	Anneal Rough Machined Kit #1 T=1900 F	
3	Anneal Rough Machined Kit #2 T=1850 F	
4	Machine	Drift Tube and Back Plate Cooling Passages Bore Coupling Cap Nipple Holes
5	Clean	Drift Tube Cylinders, Backing Plates, and Cavity End Half-Cells
6	Frist Braze	Assemble Drift Tube Cyl's. and Backing Plate/Half-Cell Assy. Braze T=1900 F
7	Leak Check	Drift Tube Cyl. Assy.'s and Backing Plate/End Half-Cell Assy.'s
8	Machine	Drift Tube Profiles/Stem Holes and Coupling Block/End Half-Cell Braze Surfaces
9	Clean	Drift Tube/Cavity Ring Assy. Pcs., Flanges, Coupling Assy. Pcs., Glidcop Disks, and Fittings
10	Second Braze	Drift Tube/Cavity Ring Assy.'s, and Coupling cavity/Coupling Cap Assy.'s
11	Leak Check	Drift Tube/Cavity Ring Assy.'s, and Coupling cavity/Coupling Cap Assy.'s
12	Machine	Finish Coupling Cavity/Slot and Accelerating End Cavity Add Cooling Passages to Coup.Caps
13	Clean	Coupling/End Half-Cell Assy.'s, Coupling Caps, and Drift Tube Cavity Ring Assy.'s
14	Stack Tune	Perform Frequency and Coupling Measurement Make Tuing Cuts REPEAT UNTIL TUNED
15	Clean	All CCDTL I Flanged Section Parts Required for Third and Final Stack Braze
16	Third Braze	Assemble CCDTL I Flanged Section Stack and Braze with Cu/Ag (CuSil)
17	Leak Check	CCDTL I's Flanged Section
18	Flange Joint Tune	Lead Flanged Section Connected Opposite End Connected
19	Install	In-House Fabricated Strong Back into Assembly and Shipping Fixture.
20	Install	2 (Two) Sets of CCDTL I's Support Brackets and Vacuum Tank Assy.'s into Strong Back
21	Install	2 (Two) CCDTL I Flanged Sections onto Support Brackets. Hook-Up Vacuum Tanks, and Align
22	Install	Quadrupole Singlets, RF Windows, Diagnostic Beam Tube AS REQUIRED, and Hook-Up All Cooling Lines
23	Leak Check	Completed Build-Up Of 2 (Two) CCDTL I Flange Sections and Cooling System
24	Purge, seal, and Package for Shipment	
25	Inhouse Fabrication Monument System	
26	Shipment	Completed Strong Back with 2 (Two) CCDTL I Flange Sections and Monument System to Site



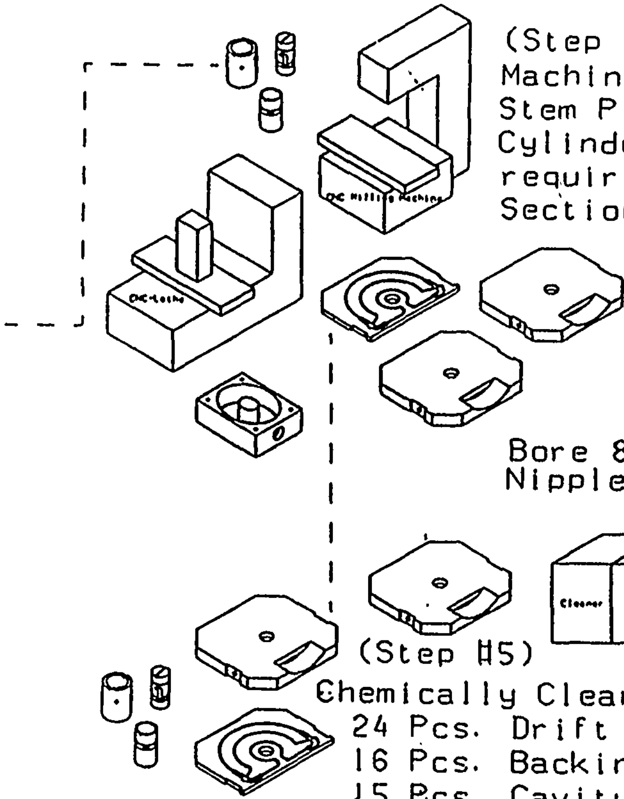
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 1



APT Room Temperature CCDTL I Flanged Section

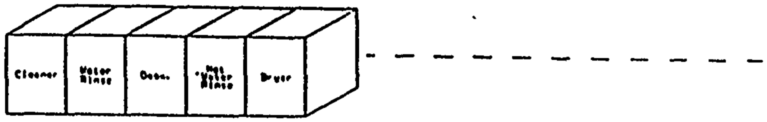
Typical In-House Manufacturing Assembly Flow - Number 2



(Step #4)
Machine Cooling Passages and Stem Pilot Holes into Drift Tube Cylinders for each Cavity Beta required for the (8) Cavity Flange Section.

Machine Cooling Passages into 15 Pcs. Backing Plates. Face Mating Surfaces between Backing Plates and Cavity End Half-Cells. Repeat Steps for 1 Pc. Flanged Cavity End Half-Cell.

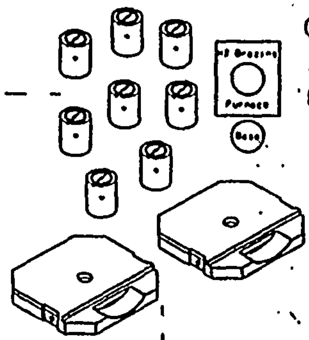
Bore 8 Pcs. Coupling Cavity Caps Confla Nipple Holes to size.



(Step #5)
Chemically Clean in Preparation for First Braze
24 Pcs. Drift Tube Cylinders
16 Pcs. Backing Platesles.
15 Pcs. Cavity End Half-Cells
1 Pc. Cavity Flanged End Half-Cell

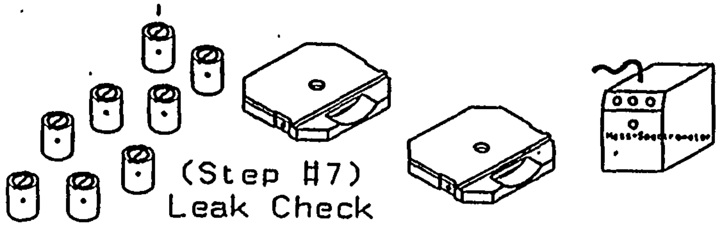
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 3



(Step #6)
Assemble into Braze Tooling with 35-65 Au/Cu Braze Material and Braze at T=1900° F.

8 Pcs. Drift Tube Sub-Assemblies using Correct Thickness of 300 SS Shim.
15 Pcs. Cavity End Half-Cell with Backing Plates.
1 Pc. Cavity Flanged End Half-Cell with Backing Plate.

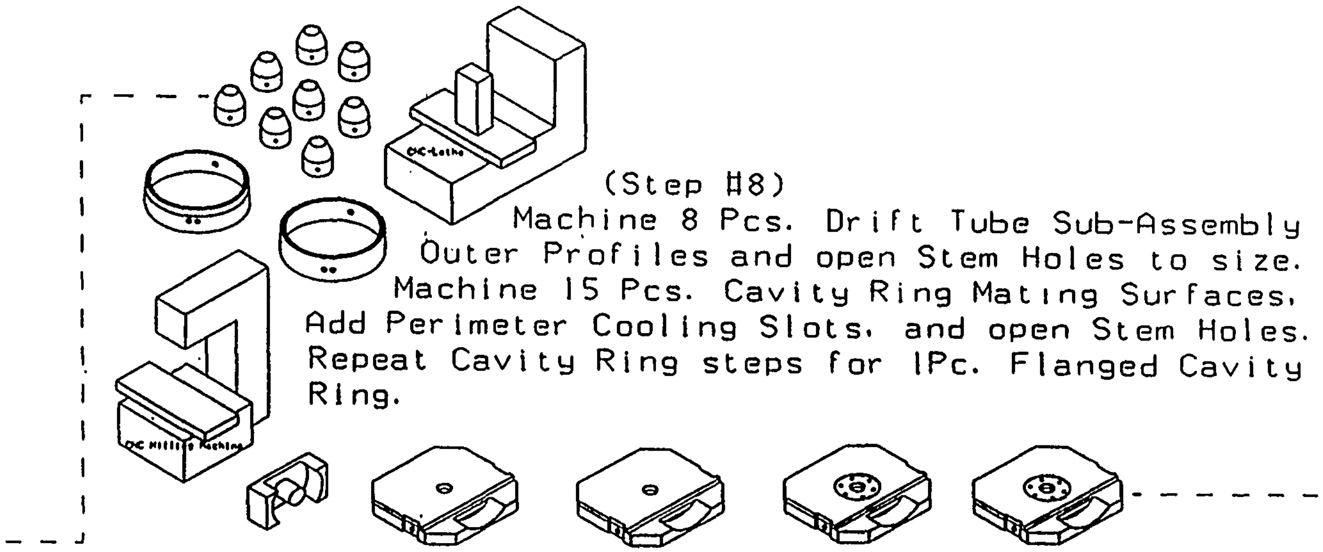


(Step #7)
Leak Check

8 Pcs. Brazed Drift Tube Assemblies
15 Pcs. Cavity End Half-Cell with Backing Plates.
1 Pc. Cavity Flanged End Half-Cell with Backing Plate.

APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 4

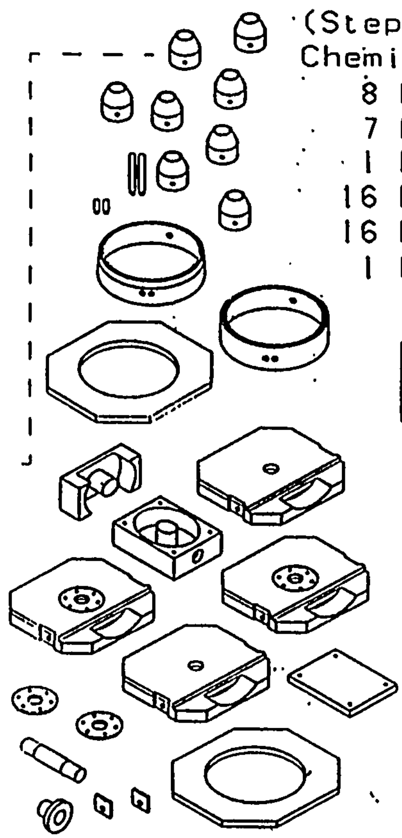


(Step #8)
Machine 8 Pcs. Drift Tube Sub-Assembly Outer Profiles and open Stem Holes to size.
Machine 15 Pcs. Cavity Ring Mating Surfaces, Add Perimeter Cooling Slots, and open Stem Holes.
Repeat Cavity Ring steps for 1Pc. Flanged Cavity Ring.

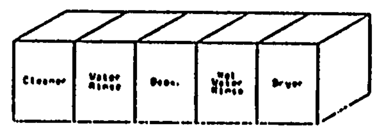
Machine 8 Pcs. End Half-Cell/Coupling Cell Sub-Assemblies.
15 Pcs. Finish Outside Surface of Backing Plates to Correct Thickness and Mating Surface of the Coupling Blocks. Bore Beam Tube/Bellows Hole to Size. NOTE AS REQUIRED 2 PCS. OF THESE WILL BE MACHINED TO EXCEPT GLIDCOP DISK AND SS THREADED INSERTS FOR BEAM TUBE DIAGNOSTICS.
1 Pc. Cavity Flanged End Half-Cell Same as Above.
8 Pcs. Finish Mating Surfaces of the Coupling Blocks.

APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 5



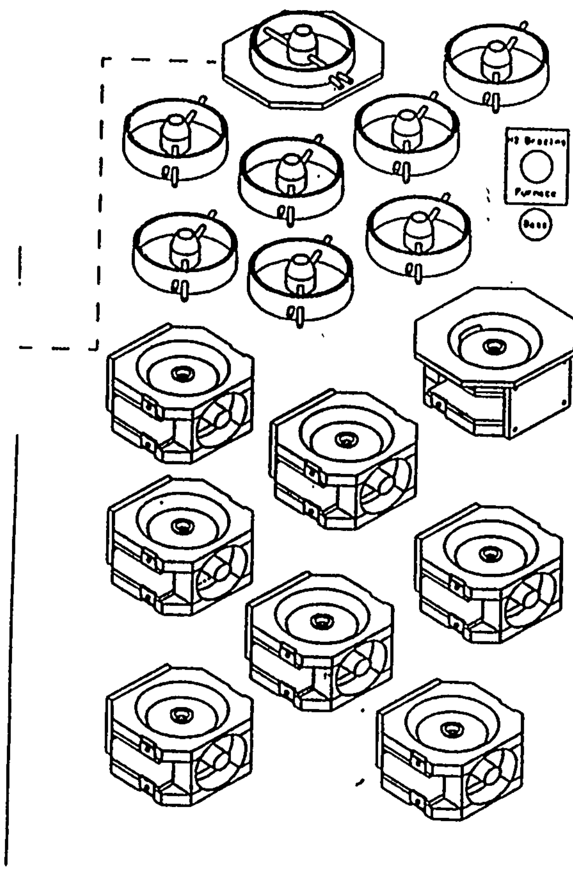
(Step #9)
Chemically Clean in Preparation for Second Braz
- 8 Pcs. Drift Tubes Sub-Assmblies
- 7 Pcs. Cavity Rings
- 1 Pc. Flanged Cavity Ring
- 16 Pcs. Cavity Ring Cooling Fittings
- 16 Pcs. Drift Tube Stems
- 1 Pc. Cavity Ring Flange



- 8 Pcs. Coupling Cavity Blocks
- 8 Pcs. Connecting Straps
- 1 Pc. Cavity Flanged End Half-Cell
- 13 Pcs. Cavity End Half-Cells
- 2 Pcs. Cavity Diagnostic End Half-Cells
- 1 Pc. Cavity End Half-Cell Flange
- 7 Pcs. SS Beam Tube/Bellows Assemblies
- 2 Pcs. Diagnostic Glidcop Disks
- 32 Pcs. SS Cooling Fittings
- 8 Pcs. Conflat Flange Nipples
- 8 Pcs. Coupling Cavity Caps
- 16 Pcs. SS Threaded Inserts

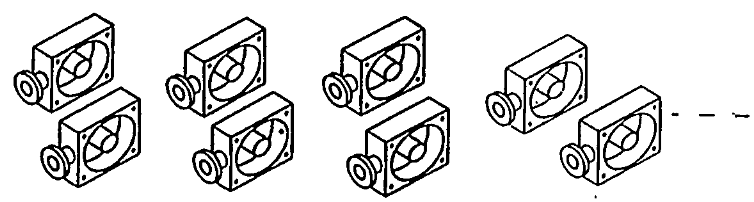
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 6



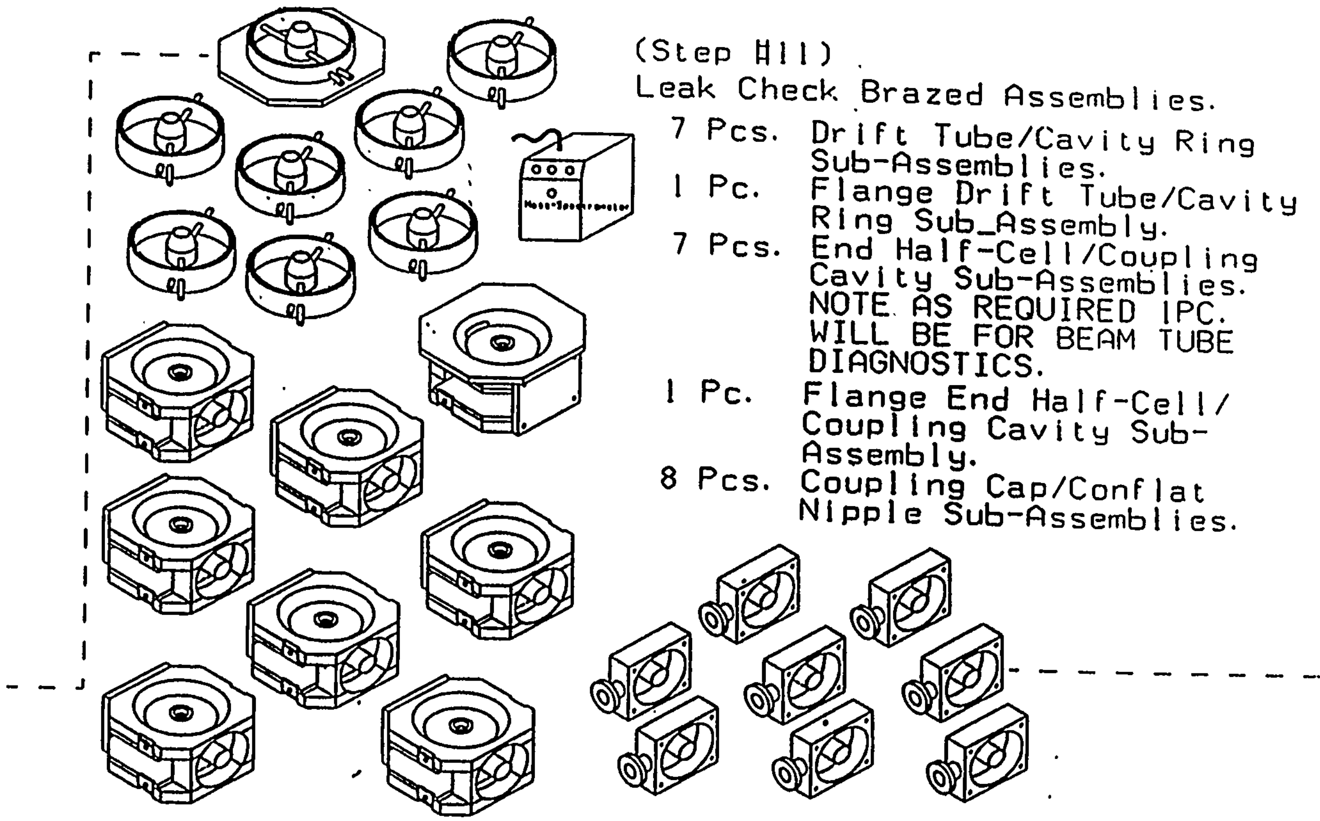
(Step #10)
Assemble Into Braze Tooling with 50-50 Au/Cu Braze Material and Braze at T=1850 F.

- 7 Pcs. Drift Tube/Cavity Ring Sub-Assemblies.
- 1 Pc. Flange Drift Tube/Cavity Ring Sub_Assembly.
- 7 Pcs. End Half-Cell/Coupling Cavity Sub-Assemblies. NOTE AS REQUIRED 1PC. WILL BE FOR BEAM TUBE DIAGNOSTICS.
- 1 Pc. Flange End Half-Cell/Coupling Cavity Sub-Assembly.
- 8 Pcs. Coupling Cap/Conflat Nipple Sub-Assemblies.



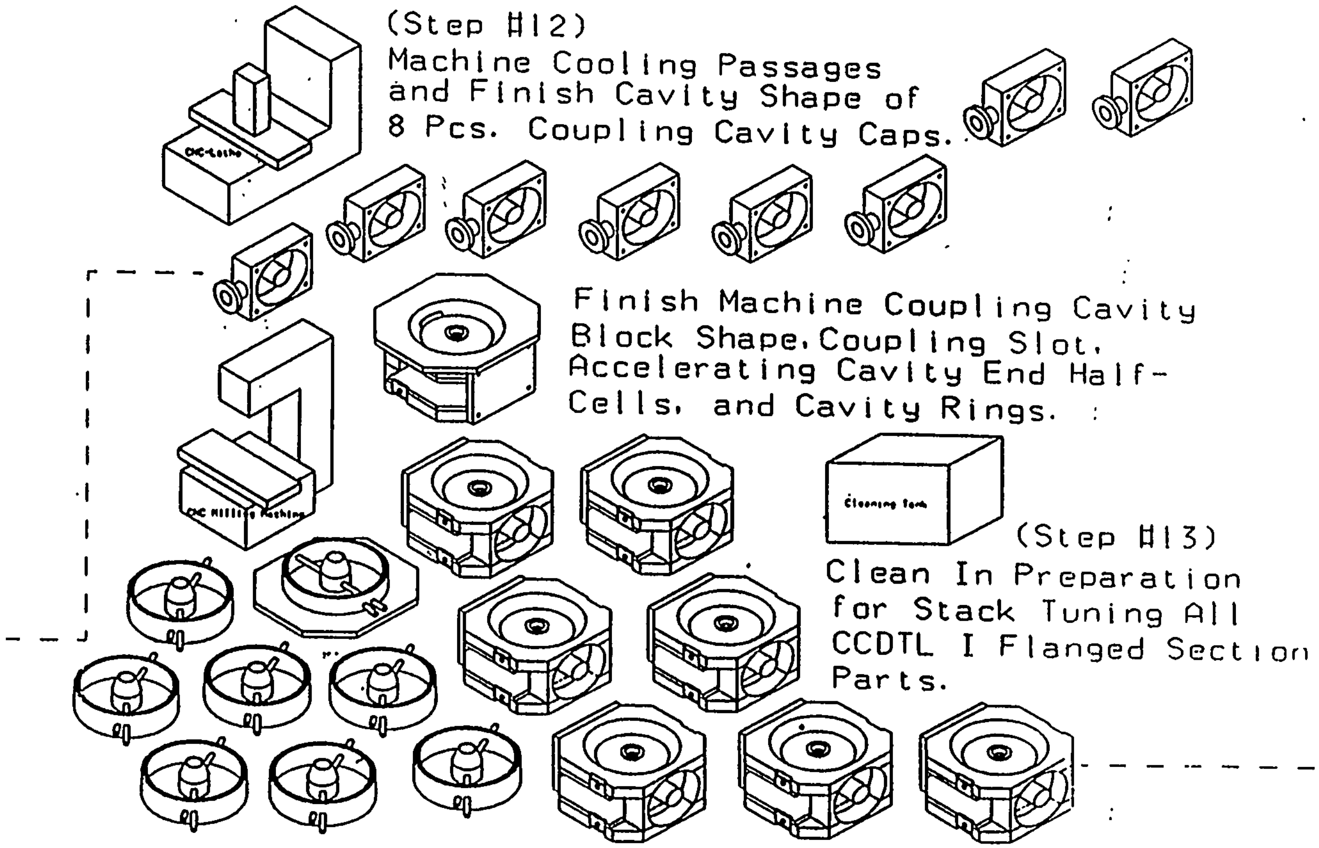
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 7



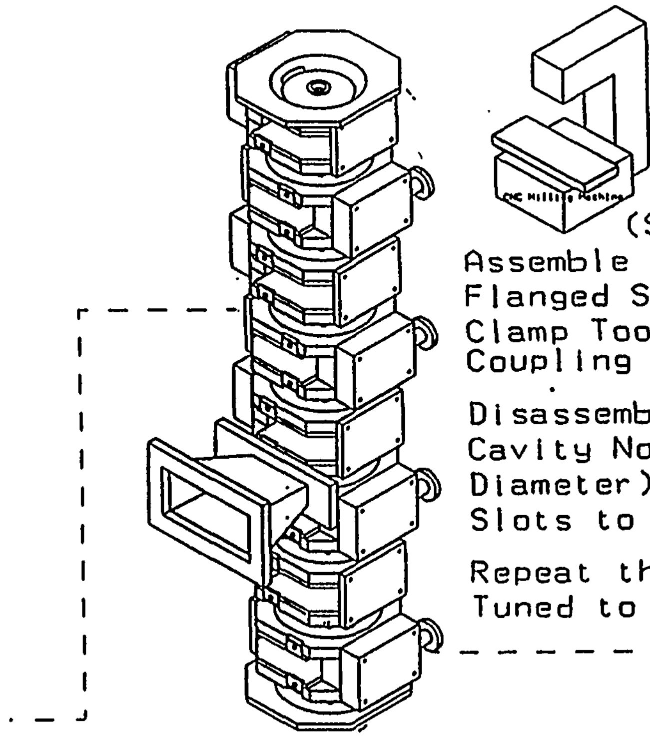
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 8



APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 9



(Step #14)

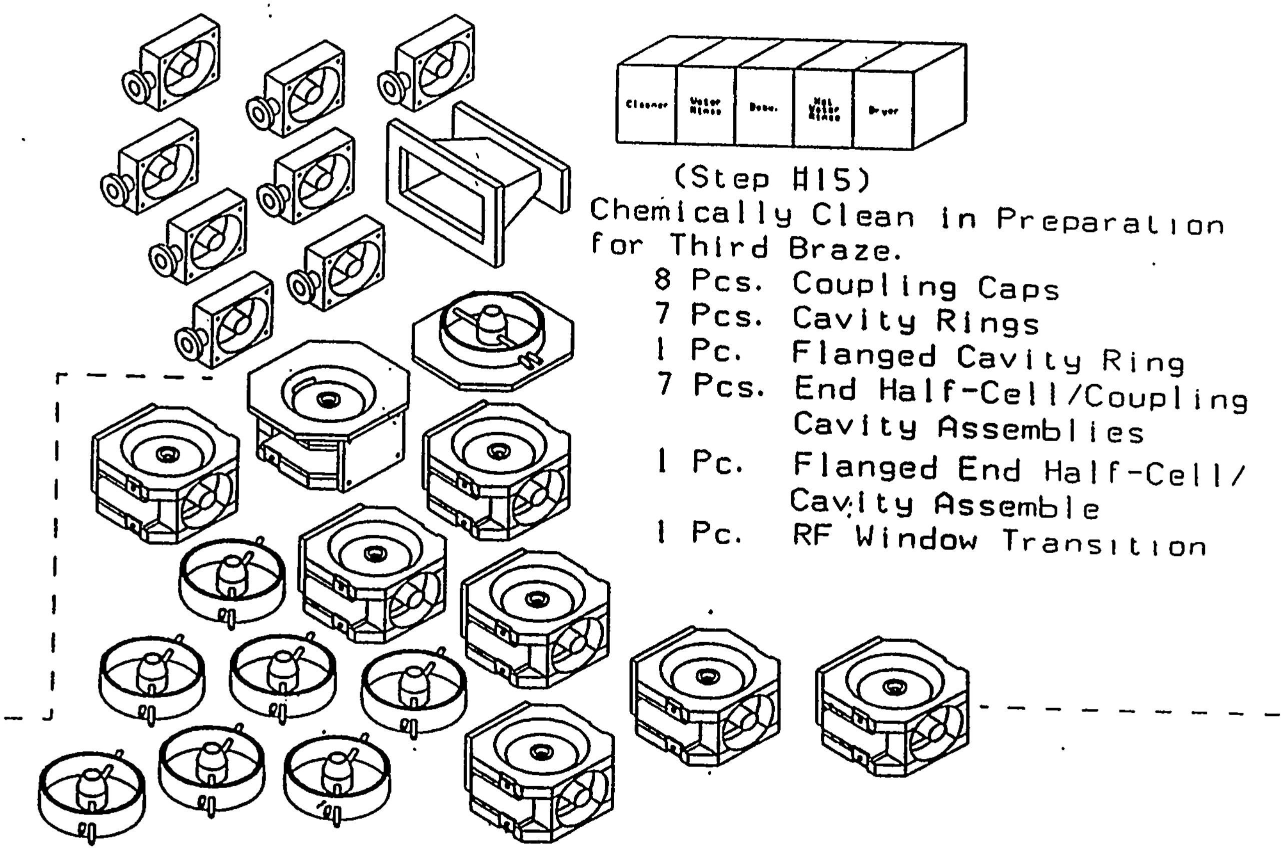
Assemble All the Pieces of CCDTL I's Flanged Section into the Stack Tuning Clamp Tool. Perform Frequency and Coupling Measurements.

Disassemble Stack and Machine Coupling Cavity Noses, Drift Tube Rings (Inner Diameter), and Cavity/Cavity Coupling Slots to Correct Frequency and Coupling.

Repeat this Procedure Until the Stack is Tuned to Correct Frequency and Coupling.

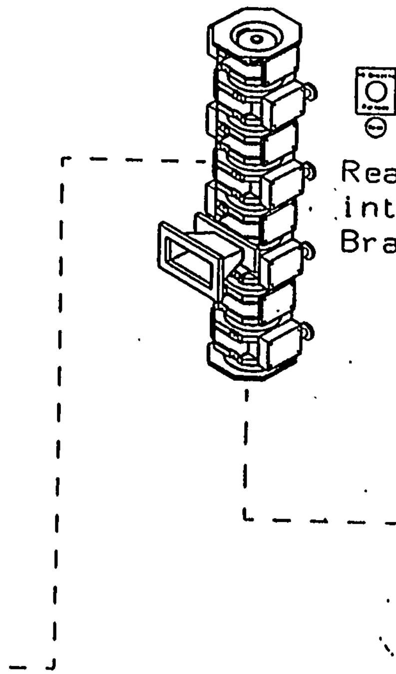
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 10

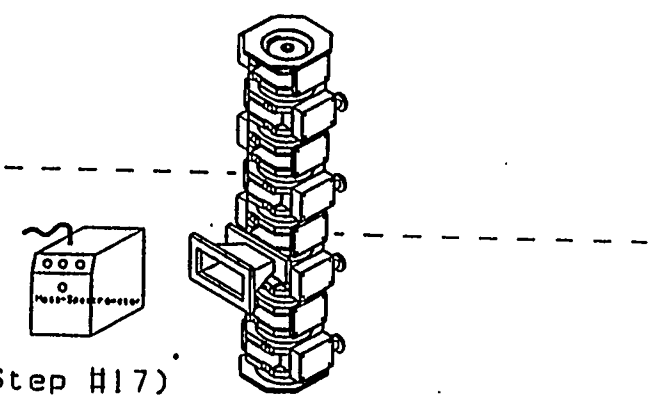


APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 11



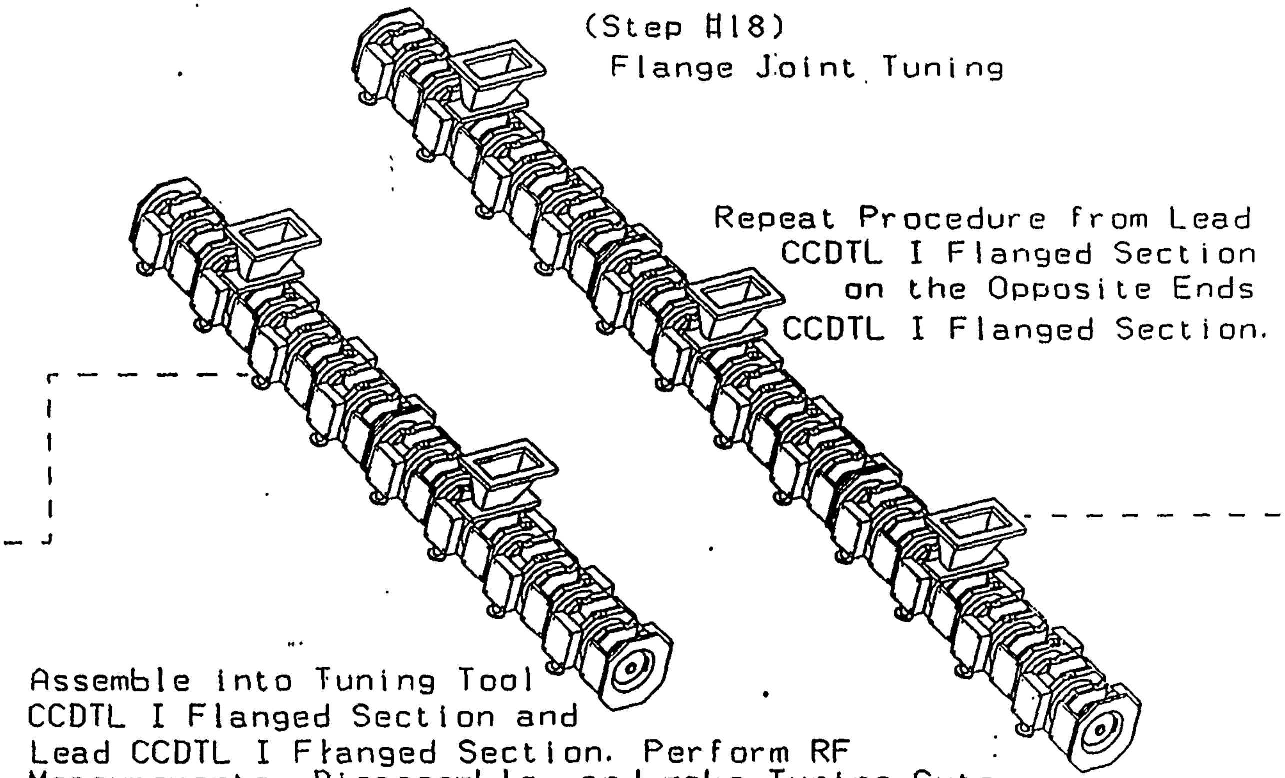
(Step #16)
Reassemble CCDTL I Flanged Section Parts into Braze Tooling with Cu/Ag (CuSil) Braze Material and Braze.



(Step #17)
Disassemble CCDTL I Flanged Section from Braze Tooling and Leak Check.

APT Room Temperature CCDTL I Flanged Section

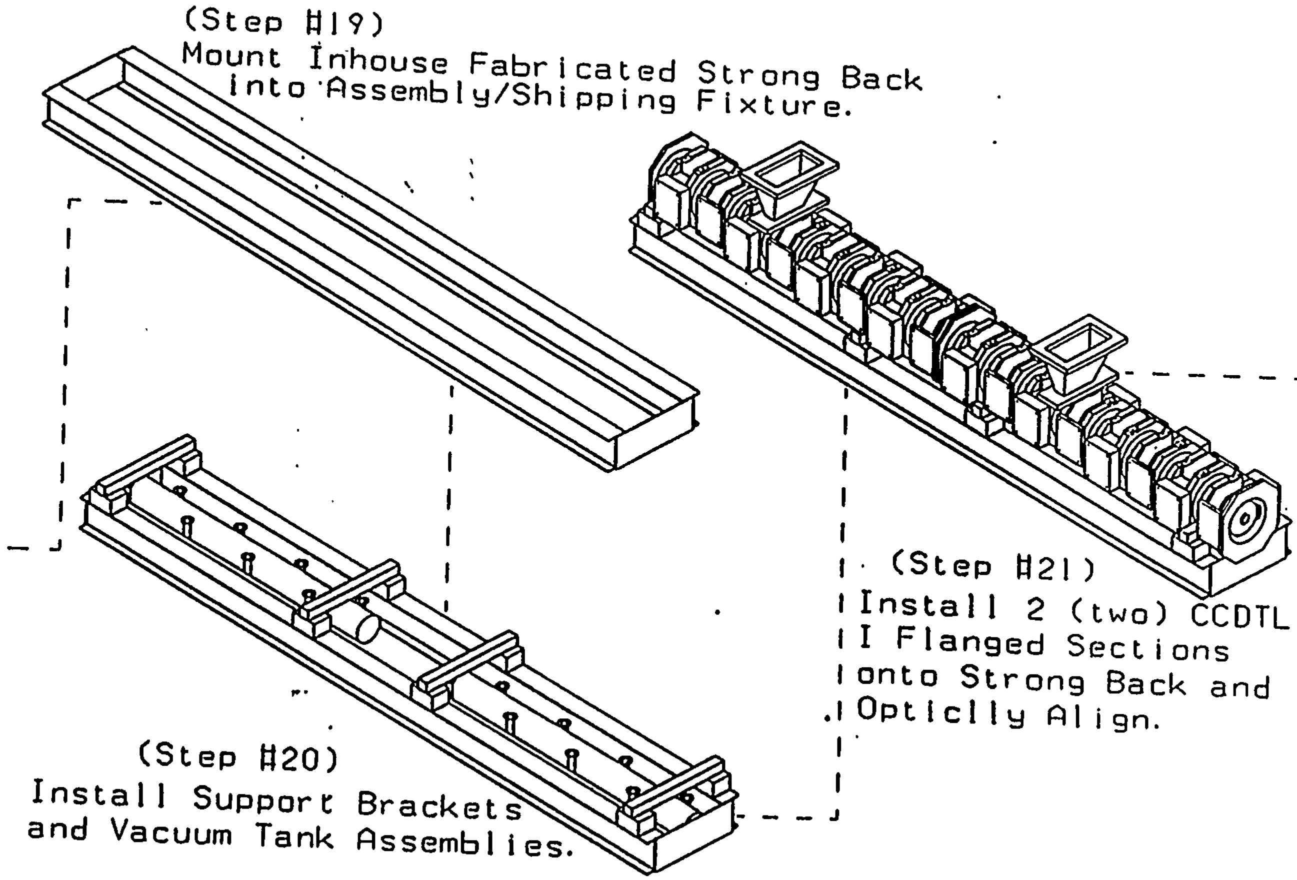
Typical In-House Manufacturing Assembly Flow - Number 12



Assemble into Tuning Tool CCDTL I Flanged Section and Lead CCDTL I Flanged Section. Perform RF Measurements. Disassemble, and make Tuning Cuts on Flanged Cavity. Repeat this Procedure Until Tuned.

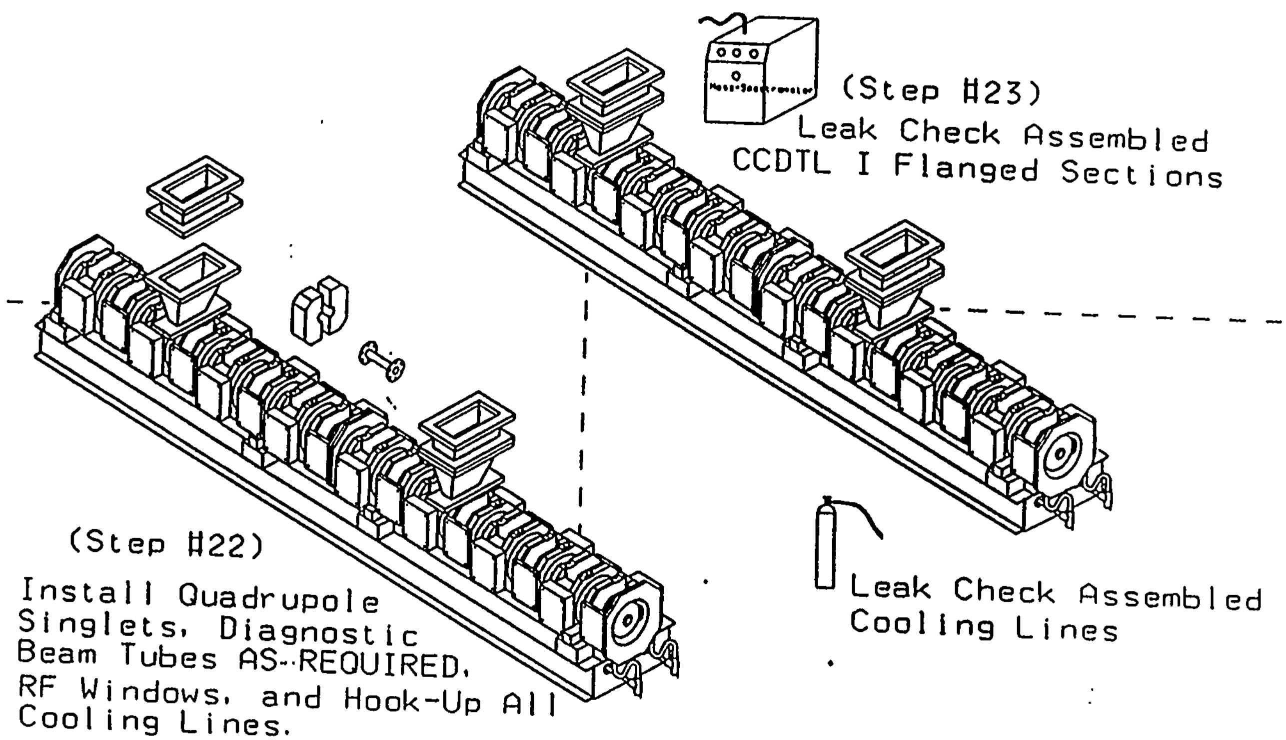
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 13



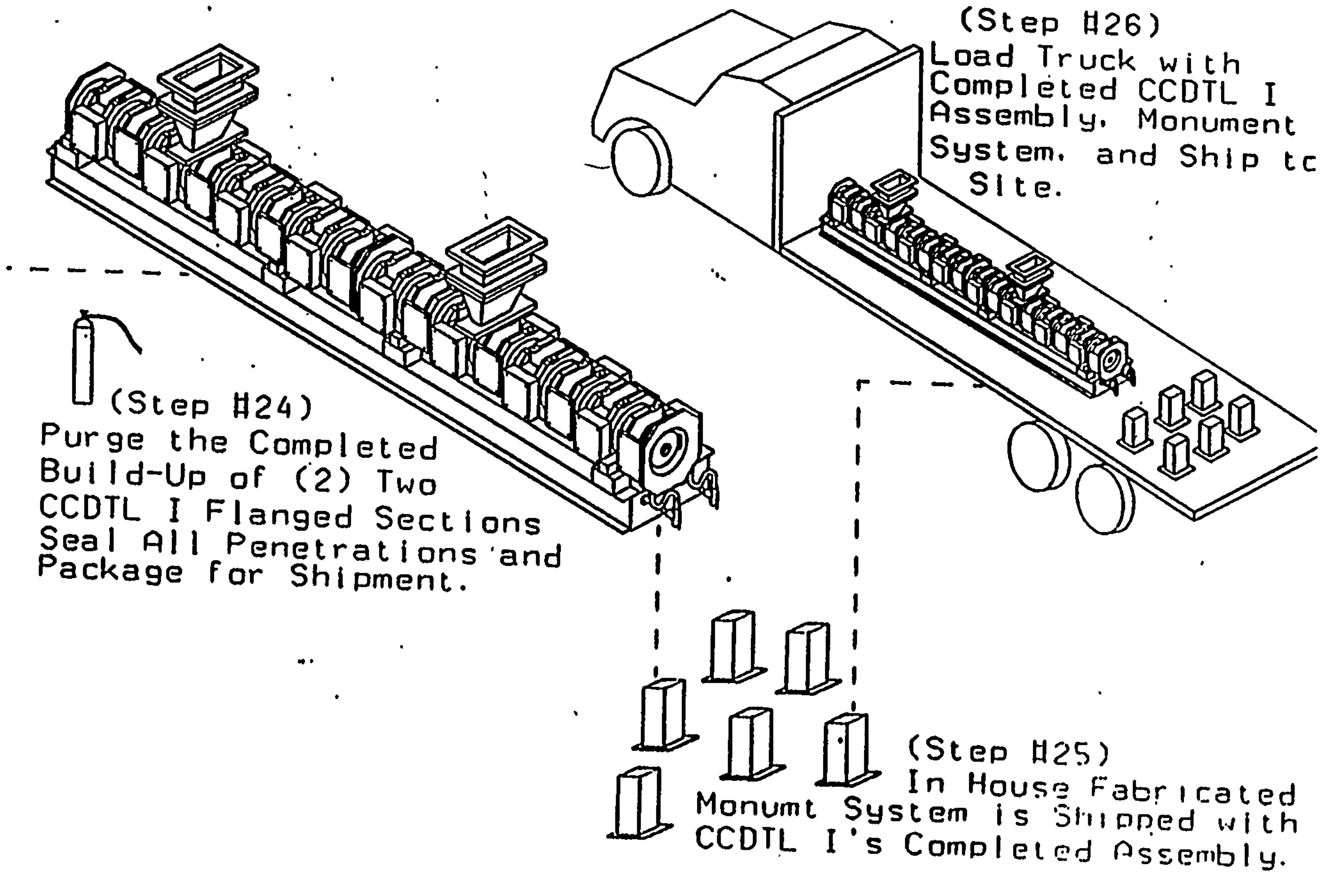
APT Room Temperature CCDTL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 14



APT Room Temperature CCDTL I Flanged Section

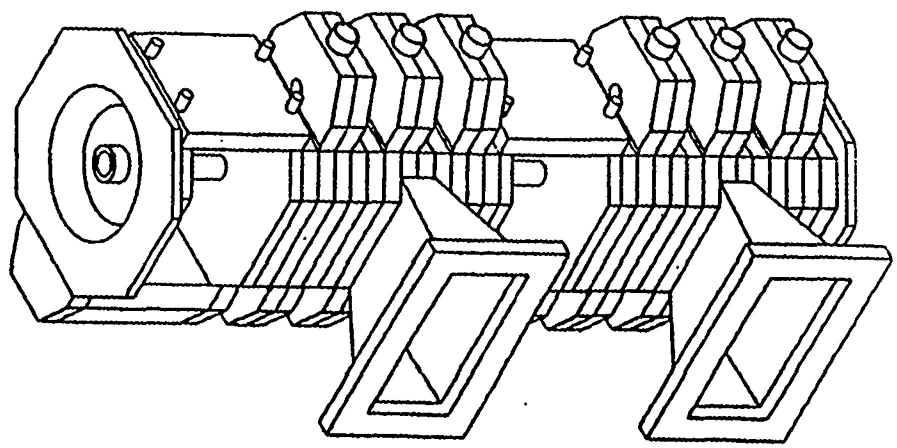
Typical In-House Manufacturing Assembly Flow - Number 15



5.1.1a Normal Conducting Accelerator Structures - CCL

Critical Path Activities for Developing a Detailed Manufacturing Plan

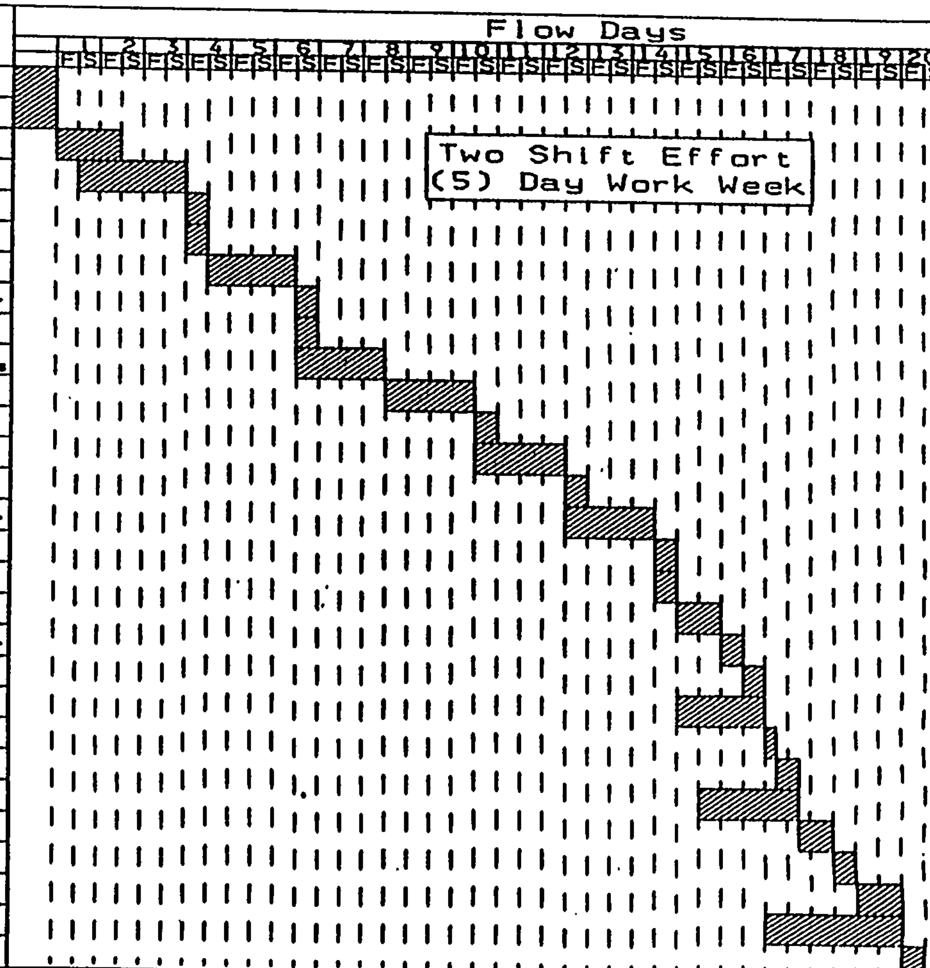
- 5 Braze Cycles for Flanged Section Build
- Leak Test After Each Braze Operation
- Strict Adherence to Cleaning, Chemical Deoxidization and Handling Procedures
- 4 Tuning Steps: 1/2 Cell Tune, Stack Tune, Measure Coupling After Cut of Drive Iris and Final Tune



APT Room Temperature CCL I Flanged Section

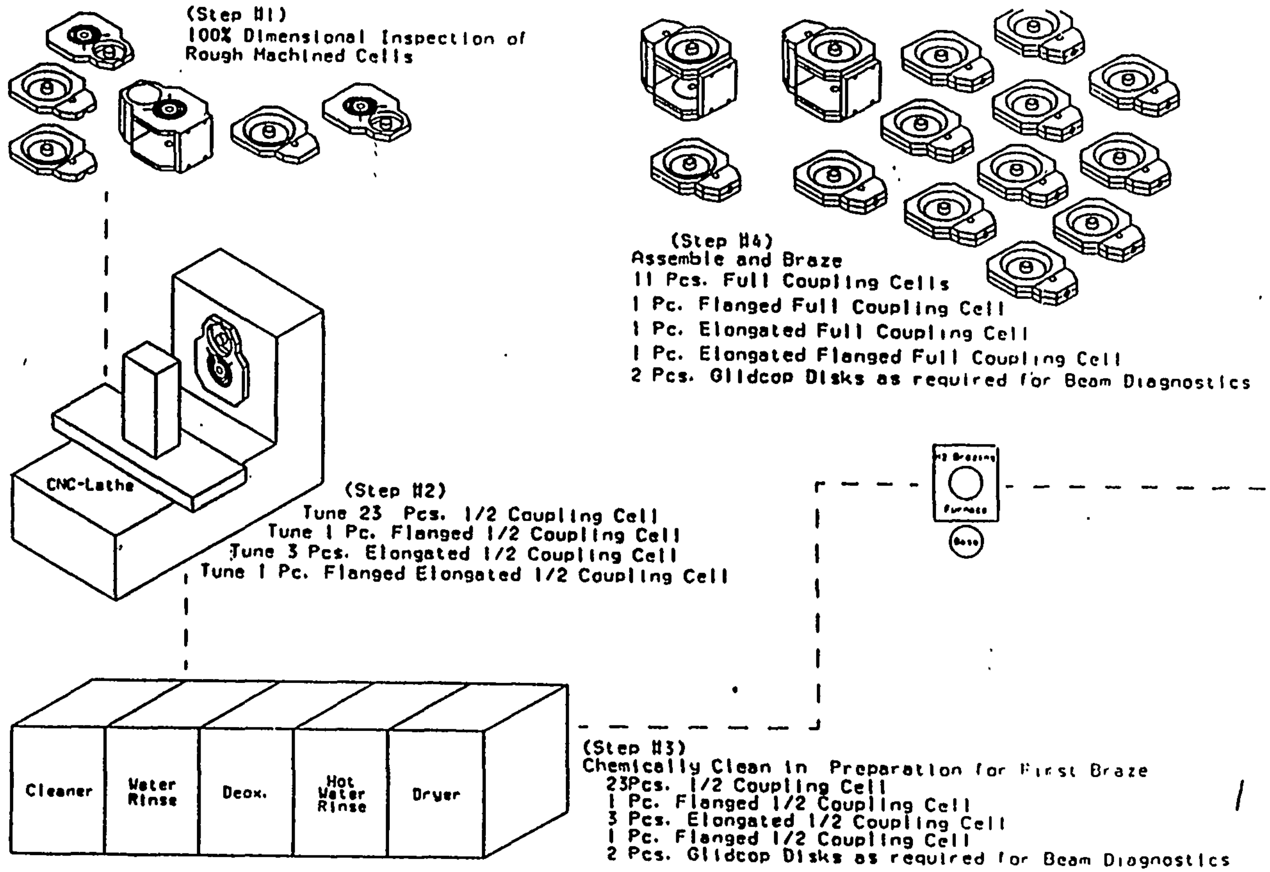
Typical In-House Manufacturing Assembly Flow

ID	Name	
—	Vendor	Receive Forging, Rough Machine, Blister Check, 100% Inspection
1	Inhouse Receiving Inspection	
2	Tune	1/2 Coupling Cells
3-4	First Braze	Clean And Assemble Into Full Coupling Cells and Gidcop Disks
5	Leak Check	Full Coupling Cells
6	Bore	Pump Down Ports To Size In Full Coupling Cells.
7-8	Second Braze	Clean And Assemble Pump Down Tubes and RF Window Assy.
9	Leak Check	Pump Down Tubes and RF Window Assy.
10	Mill	Drive Iris Rough Opening
11	Stack Tune	Mach. Nose And Tune Accel. Cells Tune Accel. Cells And Coupling Slots
12-13	Third Braze	Clean And Assemble Drive Iris Stack
14	Leak Check	Drive Iris Stack Assembly
15-16	Forth Braze	Clean And Assemble RF Window Onto Drive Iris Stack
17	Leak Check	RF Window Assembly
18-19	Final Braze	Clean And Assemble Into CCL Stack.
20	Leak Check	CCL Stack
21	Tune	Drive Coupling
22	Final Stack Tuning	
23	Orbital Weld	Conflat Nipples to Pump Down Tubes.
24	Leak Check	Complete CCL Assembly
25	Install	In-House Fabricated Strong Back into Assembly and Shipping Fixture.
26	Install	2 (Two) Sets of CCL Support Brackets and Vacuum Tank Assy. Into Strong Back
27	Install	2 (Two) CCL Flange Sections onto Support Brackets, Hook-Up Vacuum Tank and Aling.
28	Install	Cooling Lines Manifolds and Hook-Up CCL Flange Sections Cooling Lines.
29	Install	Quadrupole Singlets/Diagnostic Tube into CCL's and Hook-Up Cooling Lines.
30	Install	RF Windows onto CCL's and Conflat Flange Caps or Diagnostics onto Conflat Nipples.
31-32	Leak Check	Complete Build-Up of 2 (two) CCL Flange Sections and Cooling Lines.
33	Inhouse Fabrication	Monument System
34	Shipment	Package Complete Build-up of 2 (Two) CCL Flange Sections. Monument System and Ship



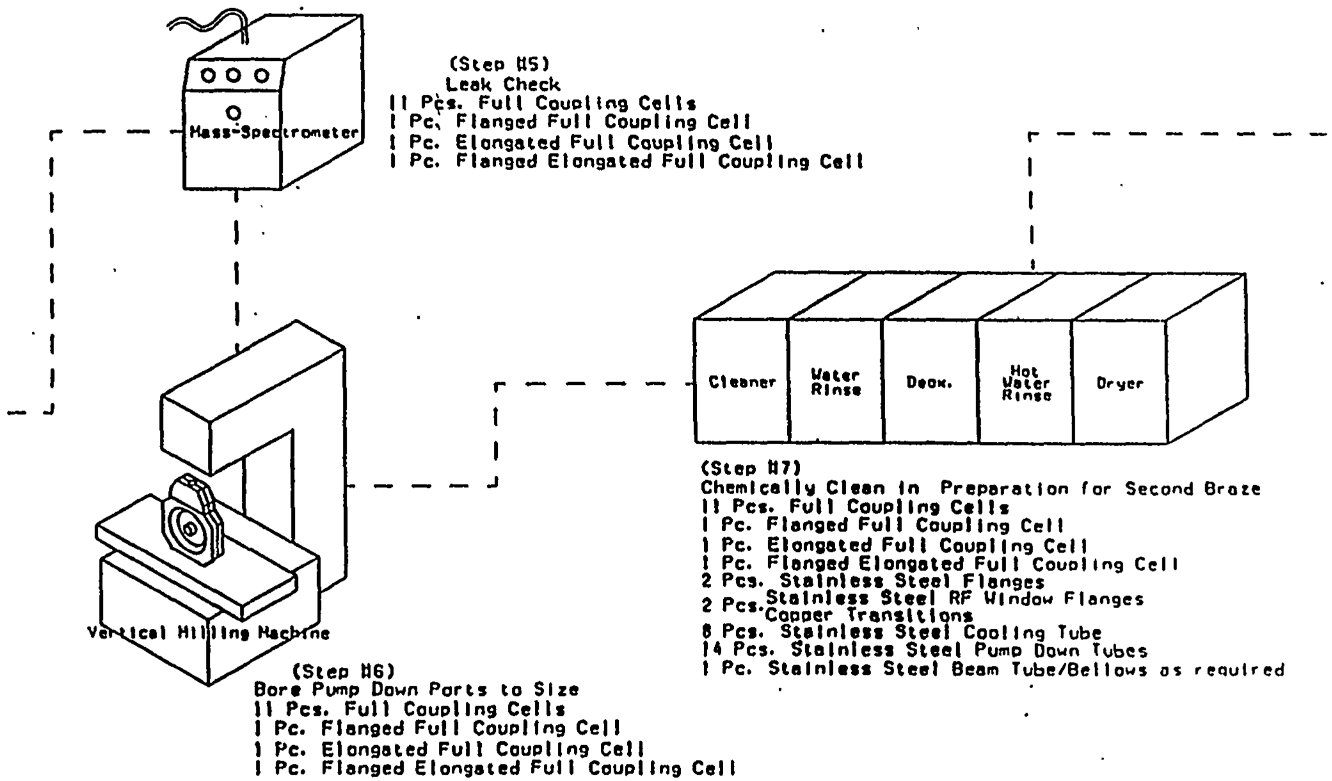
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 1



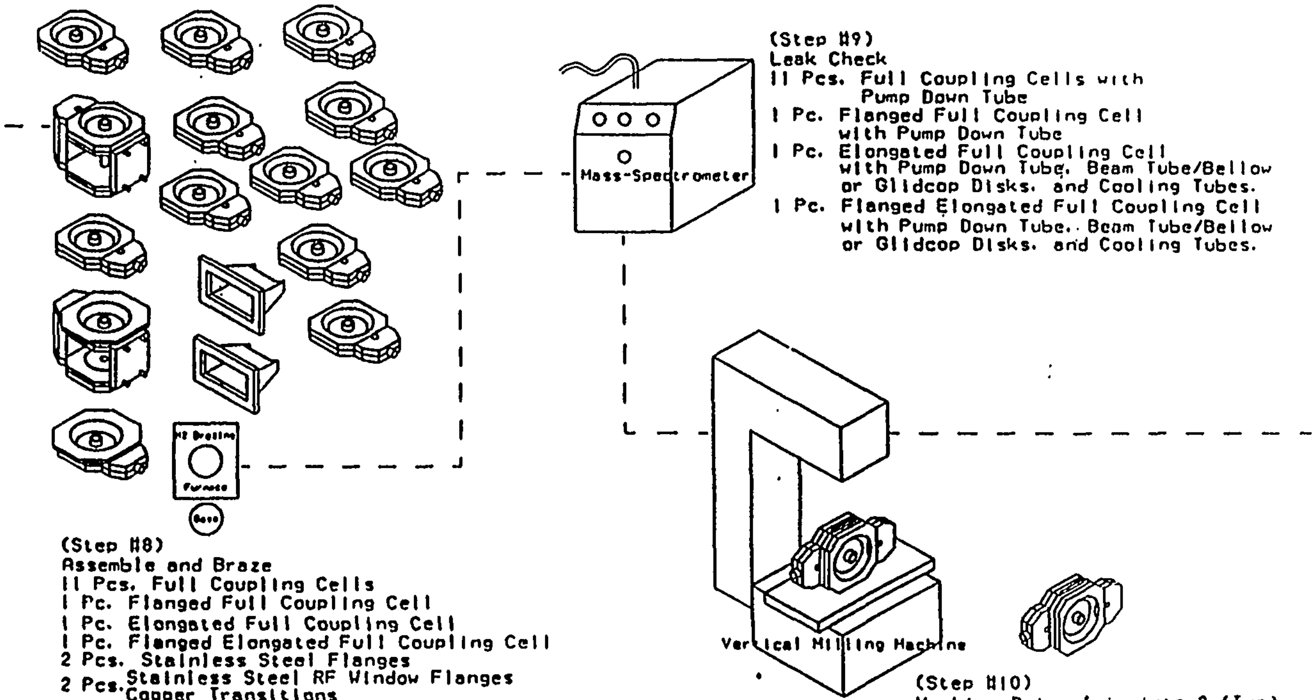
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 2



APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 3



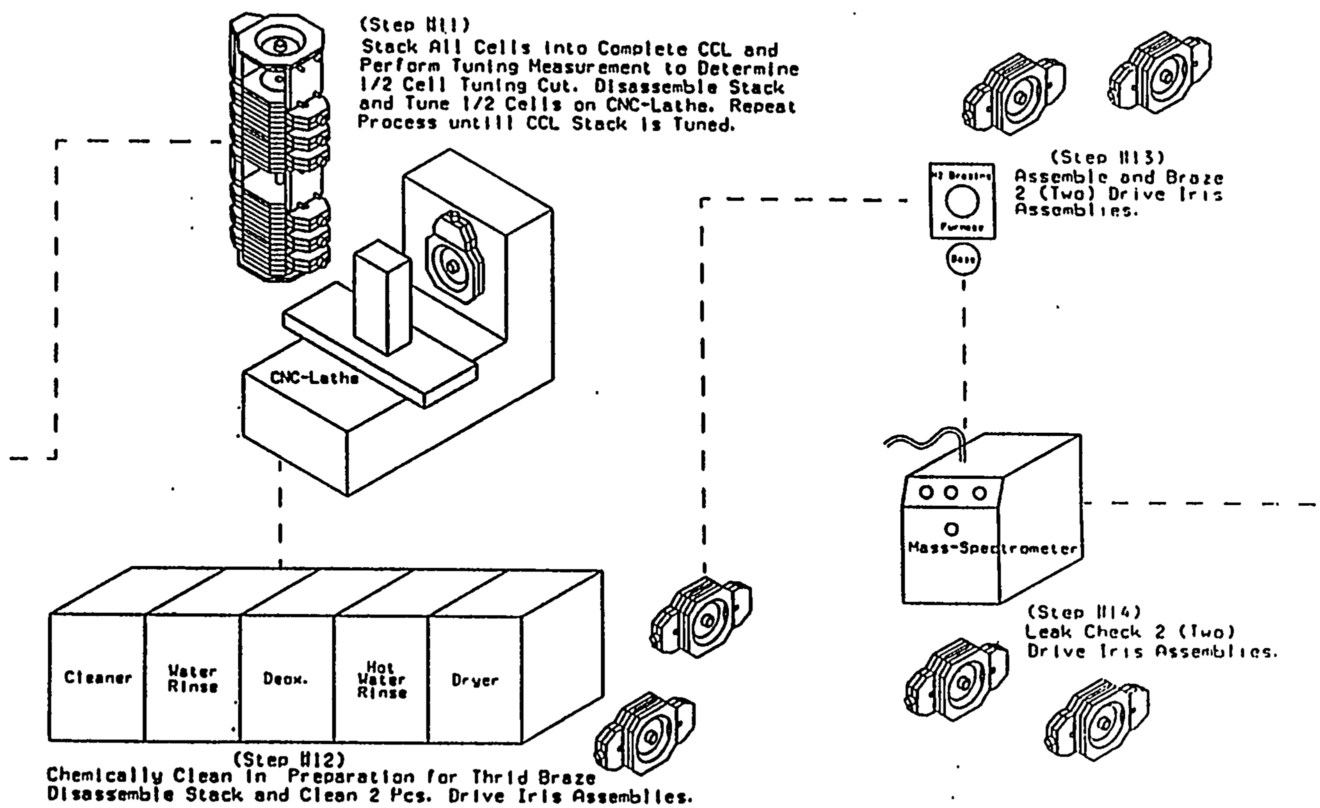
(Step #8)
Assemble and Braze
11 Pcs. Full Coupling Cells
1 Pc. Flanged Full Coupling Cell
1 Pc. Elongated Full Coupling Cell
1 Pc. Flanged Elongated Full Coupling Cell
2 Pcs. Stainless Steel Flanges
2 Pcs. Stainless Steel RF Window Flanges Copper Transitions
8 Pcs. Stainless Steel Cooling Tube
14 Pcs. Stainless Steel Pump Down Tubes
1 Pc. Stainless Steel Beam Tube/Bellows as required

(Step #9)
Leak Check
11 Pcs. Full Coupling Cells with Pump Down Tube
1 Pc. Flanged Full Coupling Cell with Pump Down Tube
1 Pc. Elongated Full Coupling Cell with Pump Down Tube, Beam Tube/Bellow or Glidcop Disks, and Cooling Tubes.
1 Pc. Flanged Elongated Full Coupling Cell with Pump Down Tube, Beam Tube/Bellow or Glidcop Disks, and Cooling Tubes.

(Step #10)
Machine Drive Iris into 2 (Two) Assembled Accelerating Cells

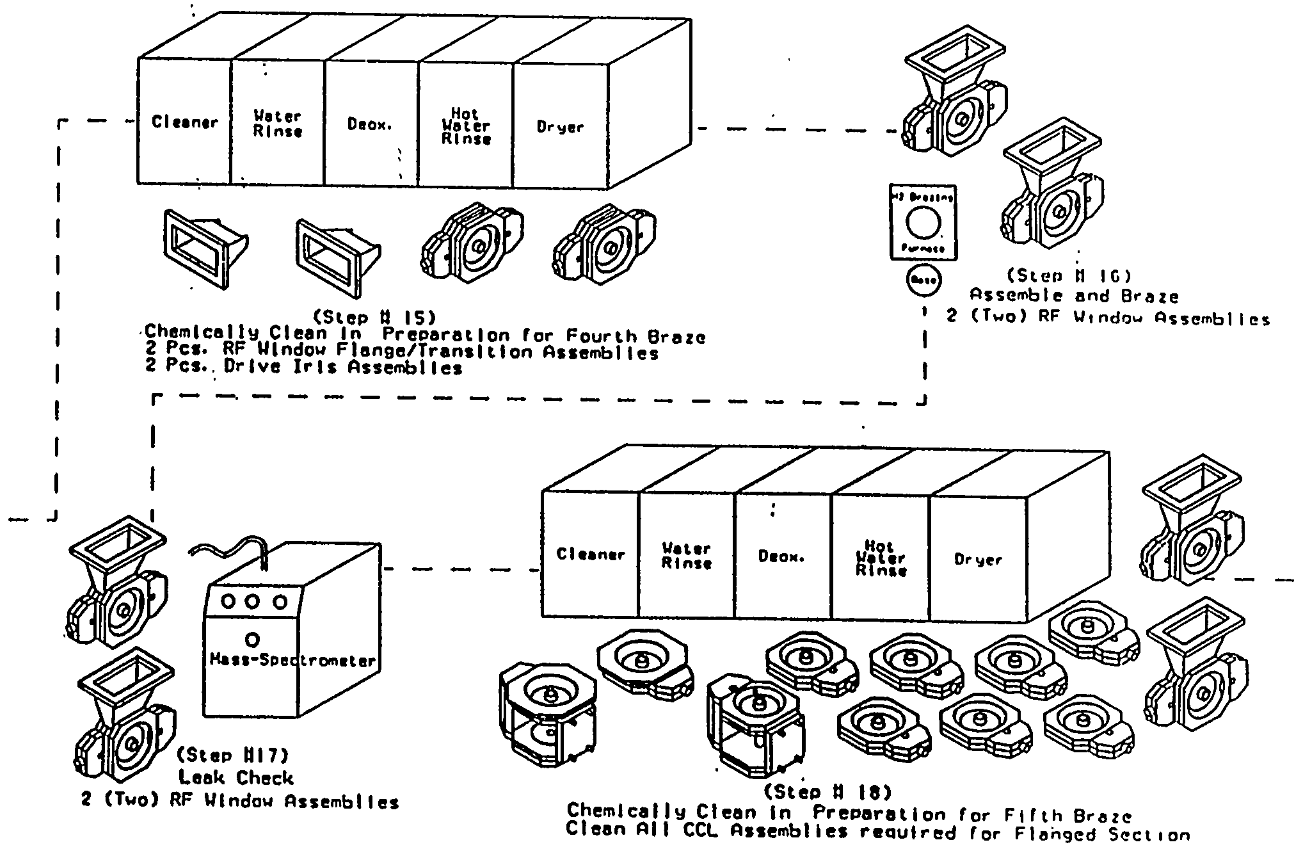
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 4



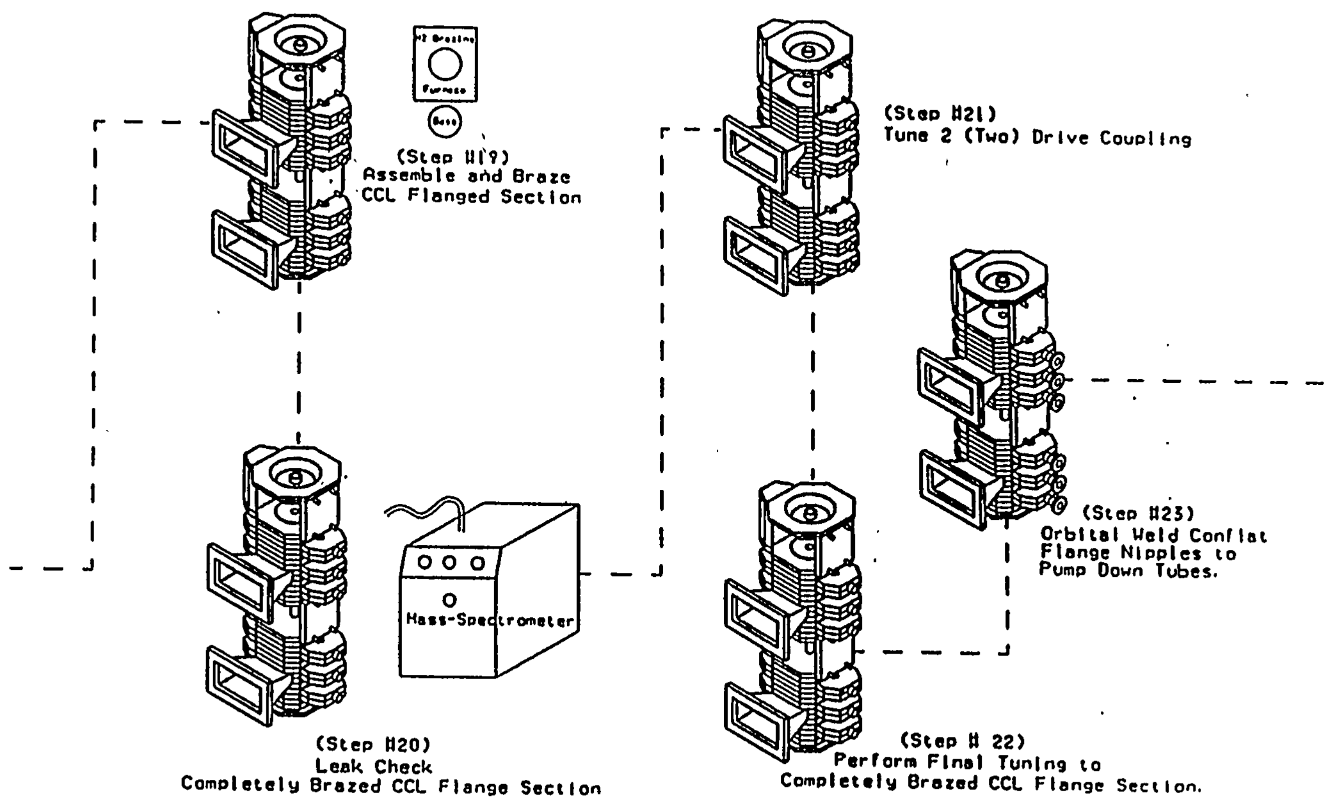
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 5



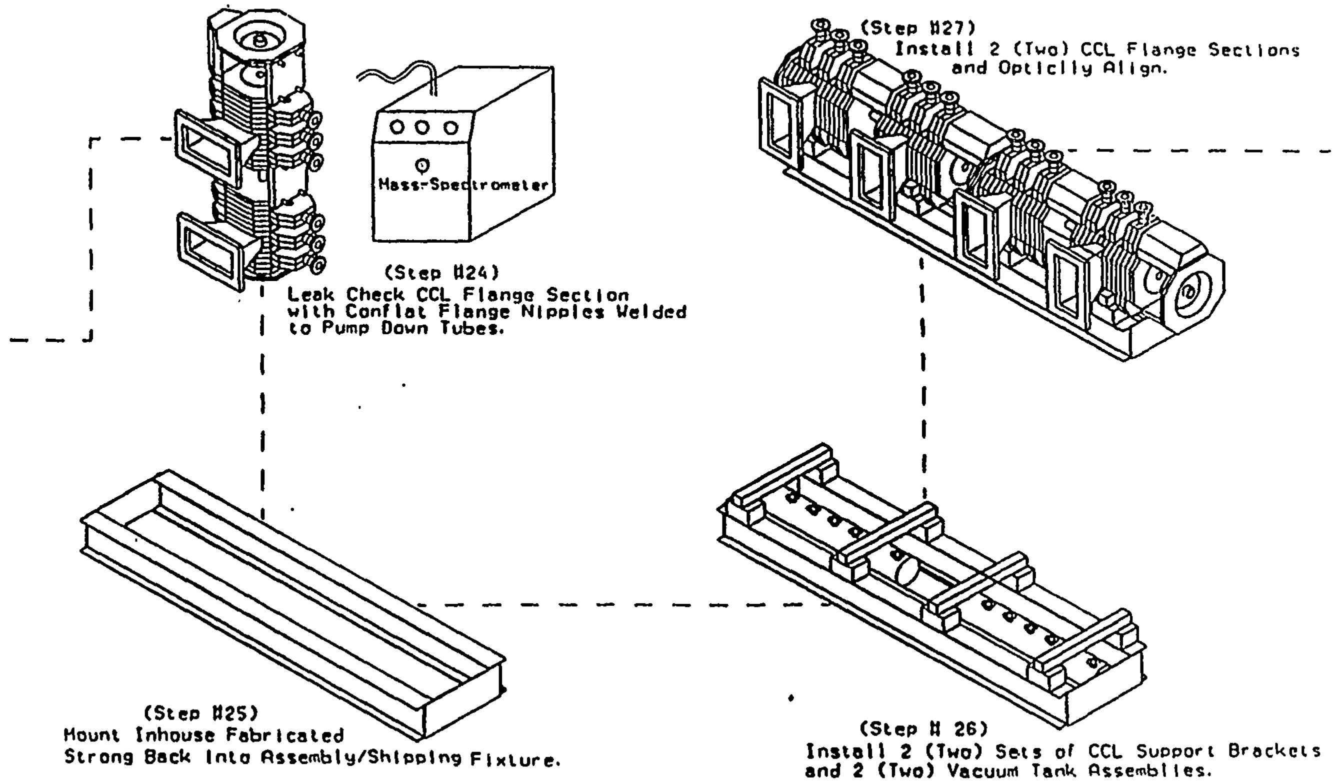
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 6



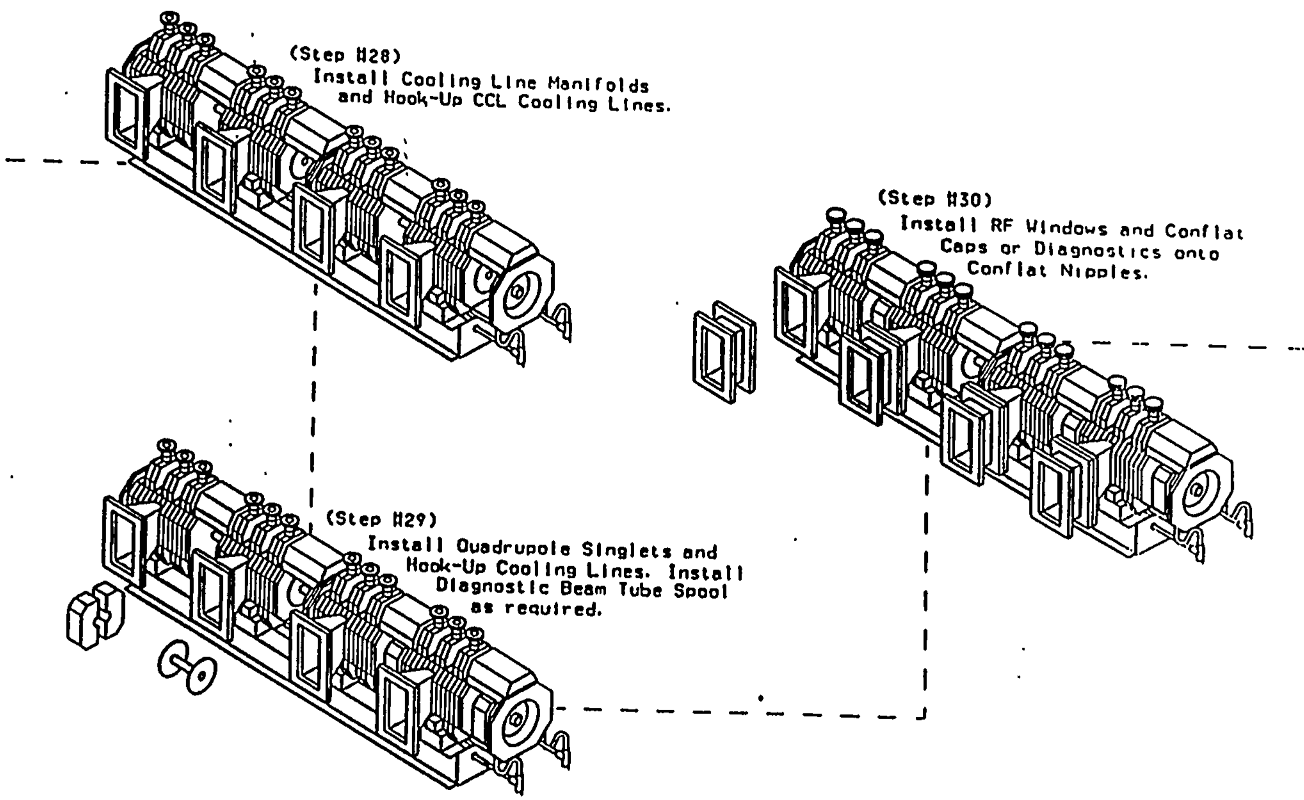
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 7



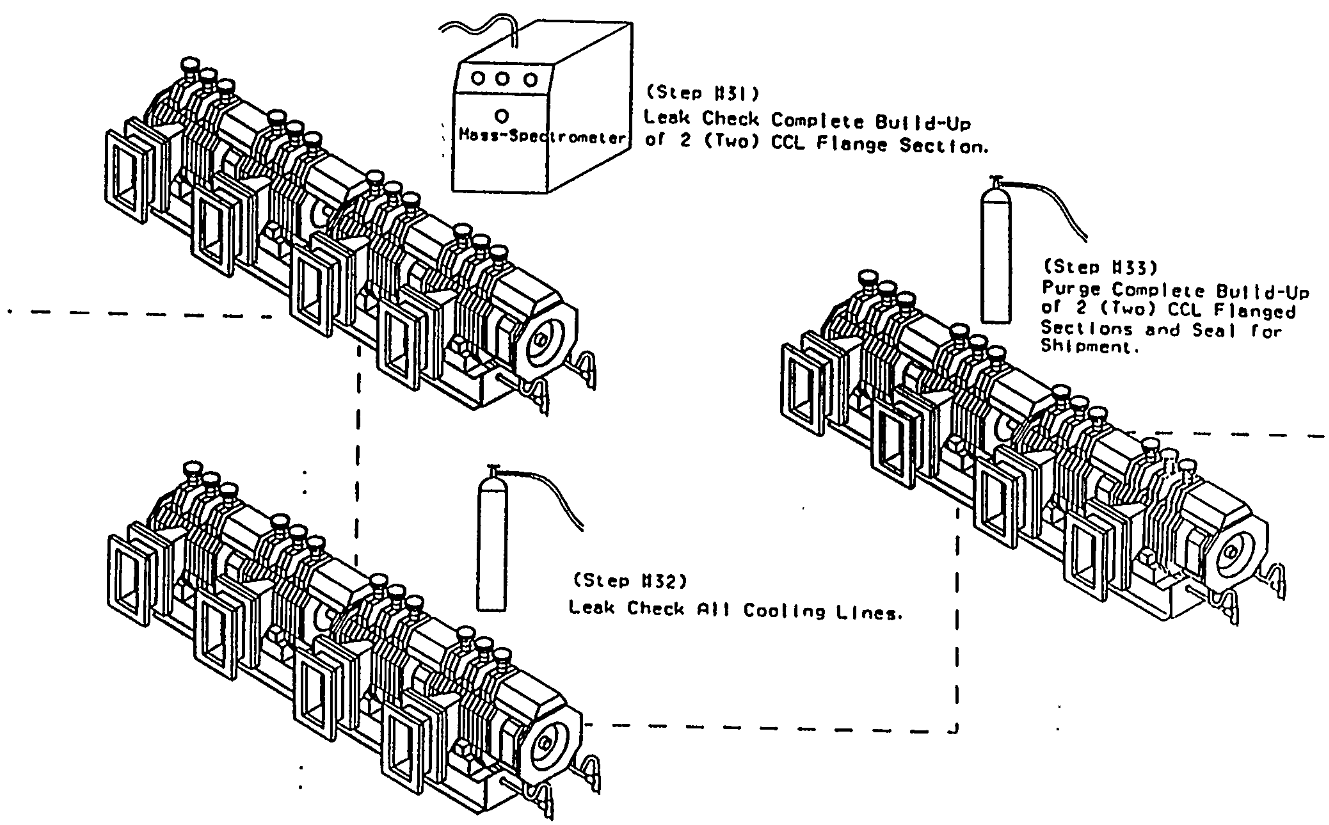
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 8



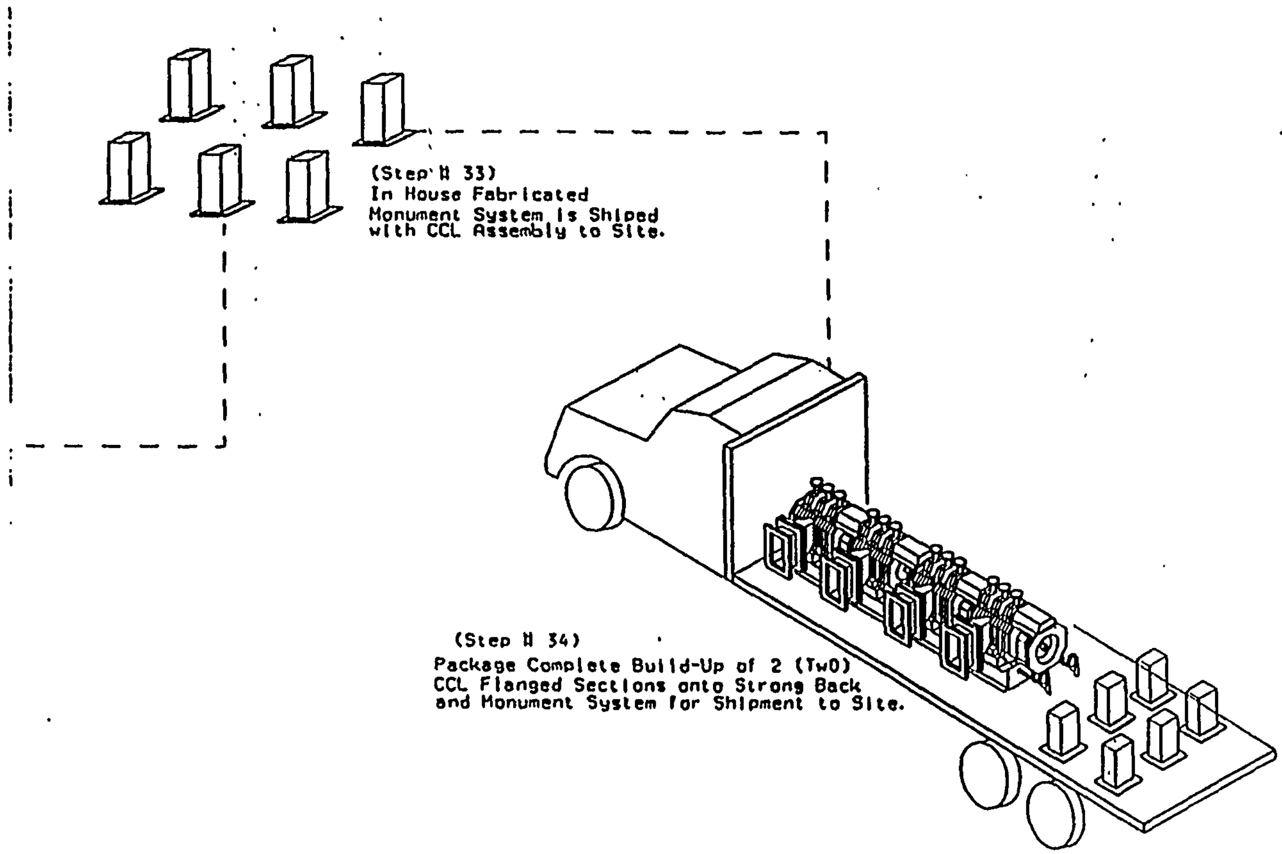
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 9



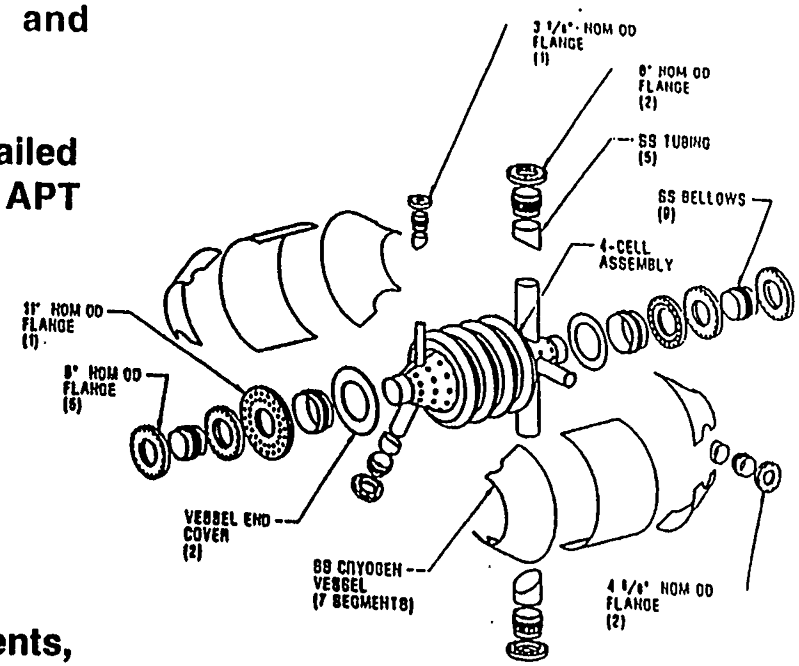
APT Room Temperature CCL I Flanged Section

Typical In-House Manufacturing Assembly Flow - Number 10



5.1.2 Superconducting Accelerator Structures

Superconducting Cryomodule Sub-Assembly and Final Assembly Integration

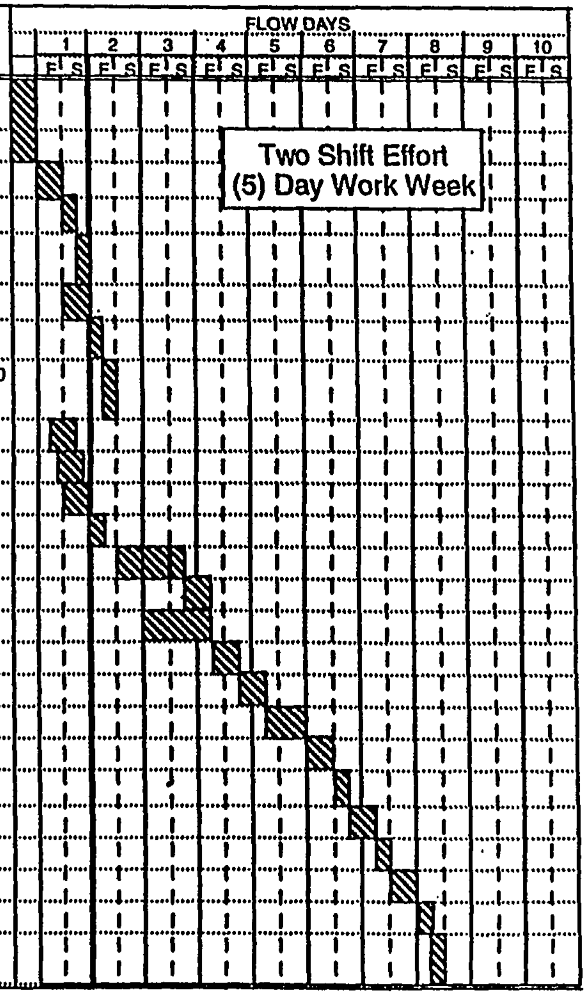


- Critical path activities for developing a detailed manufacturing plan for assembly of the APT Cryomodule include:
  1. Forming of half cells and machining of inter-locking joint
  2. Electron beam welding
  3. Buffered chemical polishing
  4. Maintaining cleanliness requirements of a class 100 clean room during assembly process.
- As we tailor our plan to meet APT requirements, we will investigate semi-automated cleaning processes such as high pressure water rinse, and improved agitation of chemical solutions.
- Manufacturing issues such as prediction of E.B. Weld Beam and Niobium shrinkage will also be addressed

APT Superconducting Cryomodule

Typical In-House Manufacturing Flow For Unit #30

ID	Name
	Vendor Fab. Niobium Cavity, Buffered Chemical Polishing, Leak Check, Clean To Class 100
1	Inhouse Receiving Inspection
2	Weld Cryo. Vessel # 1. Clean Parts, Assem. Into Tooling, Tack And Weld.
3	Leak Check Cryogen Vessel #1
4	Clean & Flush Out Inside Of Cryo. Vessel # 1 And Cap. Clean Outside Surface To Class 100 And Bag.
5	Weld Cryo. Vessel # 2, Clean Parts & Assem . Into Tooling, Tack And Weld.
6	Leak Check Cryogen Vessel #2
7	Clean & Flush Out Inside Of Cryo. Vessel #2 And Cap. Clean Outside Surface To Class 100 And Bag.
8	Clean To Class 100 All Rf Drive Line Parts And Bag For Storage.
9	Assemble Four (4) Rf Drive Line Assy.
10	Leak Check Four (4) Rf Drive Line Assemblies And Bag For Storage.
11	Clean To Class 100 All Remaining Parts Required For Cryomodule Subassembly.
12	Assemble Cryomodule Subassembly, Make All Beam Line Adjustments To Cavities.
13	Leak Check Cryomodule Subassembly, Evacuate And Seal Cavity Assy, Bag For Storage
14	Clean/Class 100,000 Parts Req. For Cryomodule Final Assy., Bag For Storage.
15	Assembly Stage #1. Inspect Installation.
16	Assembly Stage #2. Inspect Installation, Check Adjustments, Test Operation
17	Assembly Stage #3. Inspect Installation, Check Adjustments, Test Operation.
18	Assembly Stage #4. Inspect Installation, Leak Check, Purge And Seal.
19	Assembly Stage #5. Inspect Installation, Leak Check, Purge And Seal.
20	Assembly Stage #6. Inspect Installation, Leak Check, Evacuate And Seal.
21	Assembly Stage #7. Inspect Installation, Test Operation, Leak Check.
22	Assembly Stage #8. Inspect Installation, Check Adjustment. Evacuate And Seal.
23	Assembly Stage #9.Install Shipping Caps On Rf Windows, Bag For Shipment.
24	Shipment Kit Four (4) Rf Feed Line Bellows, Pkg. Kits And Cryomodule Into Crate, Ship Or Store.



Fabricate Niobium Cavity Parts

1/2 Cell:

1.Rough Cut 8Pcs. .
2.Press Form 8Pcs. Into Cavity Shape.
3.Machine 4Pcs. To Size With Female Inter Locking Joint.
4.Machine 4Pcs. To Size With Male Inter Locking Joint.

Cavity End Pipes:

1.Rough Cut 2Pcs..
2.Machine 1Pc. To Length With Female Inter Locking Joint On One (1) End .Two (2) RF Power Holes And One (1) HOM Hole.
3.Machine 1Pc. To Length With Male Inter Locking Joint On One (1) End . One (1) RF Probe Hole ,And One (1) HOM Hole.

RF Power Tubes:

1.Rough Cut 2Pcs..
2.Machine 2Pcs. To Length With Fish Mouth On One End And Male Inter Locking Joint On The Other.

Hom Tubes:

1.Rough Cut 2Pcs..
2.Machine 2Pcs. To Length With Fish Mouth On One End And Inter Locking Joint On The Other.

RF Probe Tube:

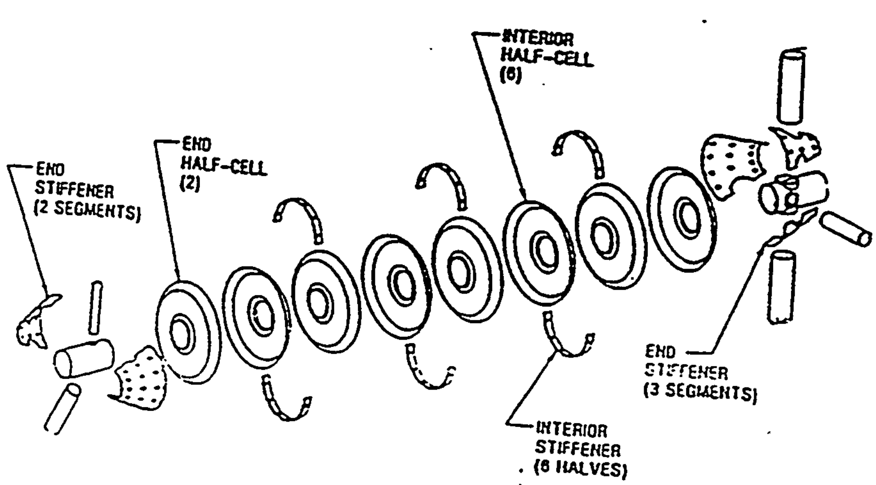
1.Rough Cut 1Pc..
2.Machine 1Pc. To Length With Fish Mouth On One End And Inter Locking Joint On The Other.

Stiffeners Between Cells:

1.Rough Cut 6Pcs. With Cooling Holes.
2.Machine 6Pcs. To Correct Width And Length.
3.Press Form 6Pcs. Into _ Circles.

Stiffeners End Cones:

1.Rough Cut Five (5) Different Shapes Required To Fabricate Two (2) End Cones.
2.Machine Each Of The 5Pcs. To Their Correct Size And Shape.
3.Press Form Each Of The 5Pcs. Segments Into Shape.



Fabricate Stainless Steel Cryogen Vessel Parts

End Covers:

1. Rough Cut 2Pcs..
2. Machine 2Pcs. To Size.

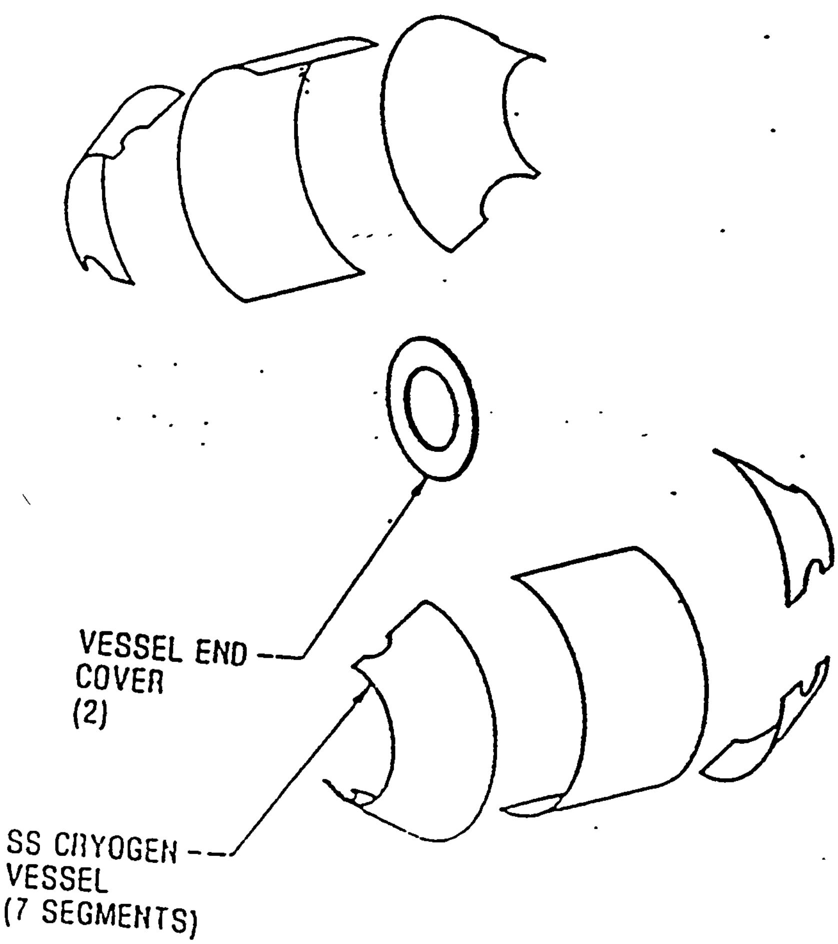
Central Cylinder:

1. Rough Cut 2Pcs..
2. Machine 1Pc. To Size With Return Port Hole.
3. Machine 1Pc. To Size With Inlet Hole.
4. Press Form 2Pcs. Into 1/2 Circles.

End Cones:

1. Rough Cut Five (5) Different Shapes Required To Fabricate Two (2) End Cones.
2. Machine Each Of The 5Pcs. To Their Correct Size And Shape
3. Press Form Each Of The Five (5) Segments Into Shape.

Manufacturing Issues
For Discussion



Purchased Parts Required
For
Niobium Cavity And Cryogen Vessel

Niobium Cavity:

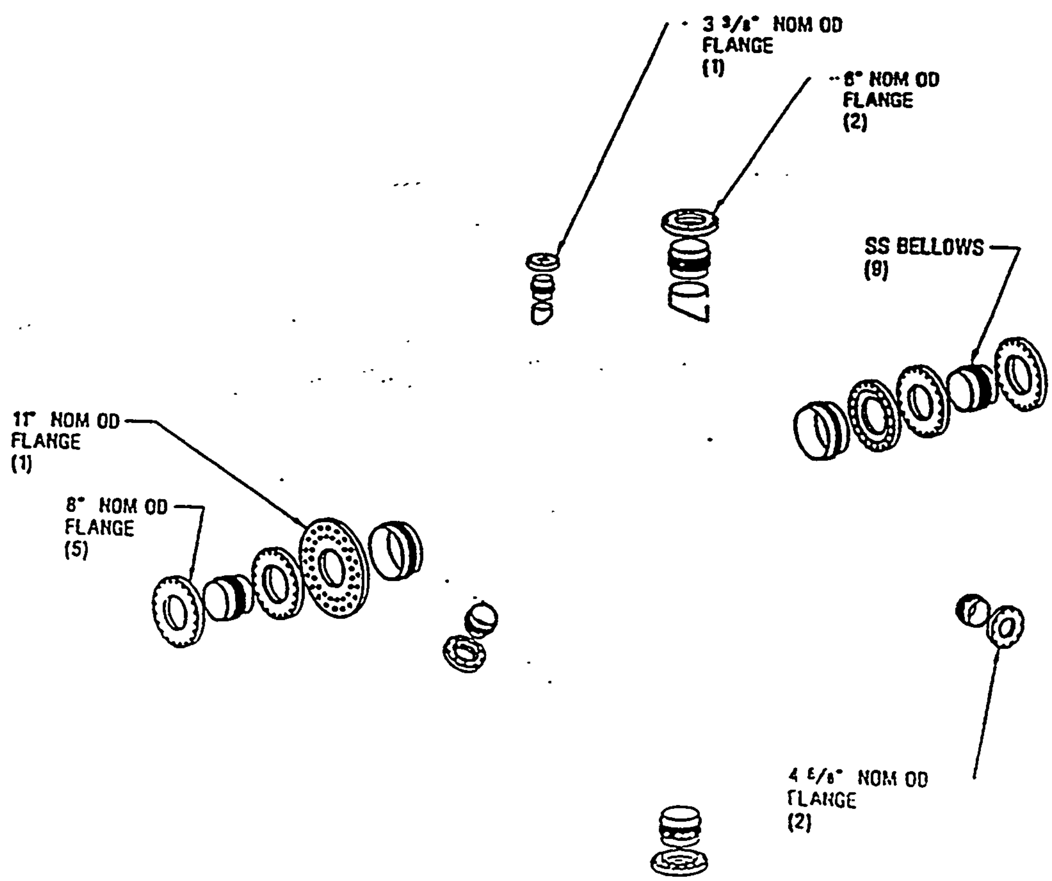
1. 8" Cavity End Flanges 2Pcs.
2. 8" Cavity End Flange And Bellows Assemblies 2Pcs..
3. 6" RF Power Tube Flange And Bellows Assemblies 2Pcs..
4. 4.625" HOM Tube Flange And Bellows Assemblies 2Pcs..
5. 3.375" RF Probe Flange And Bellows Assembly 1Pc...

Cryogen Vessel:

1. 11" Vessel End Flange And Bellows Assembly 1_Pc...
2. 8" Vessel End Flange And Bellows Assembly 1Pc...
3. Return Tee With two (2) 4.625" Flanges On The Run And One (1) Fish Mouth Tube To Fit Cryogen Cyclinder.
4. Inlet Tee With Two (2) 3.375" Flanges On The Run And One (1) Fish Mouth Tube To Fit Cryogen Cyclinder.

Manufacturing Issues
<u>For Discussion</u>

- Buying As Detail Or Assembly.



Preparation And Assembly
For Stainless Steel To Niobium
EB Weld #1

Clean Parts For Welding:
1. RF Power Tubes 2Pcs..
2. HOM Tubes 2Pcs..
3. RF Probe Tube 1Pc..
4. 6" Flange And Bellwos Assembly 2Pcs..
5. 4.625" Flange And Bellows Assembly 2Pcs..
6. 3.375" Flange And Bellows Assembly 1Pc..

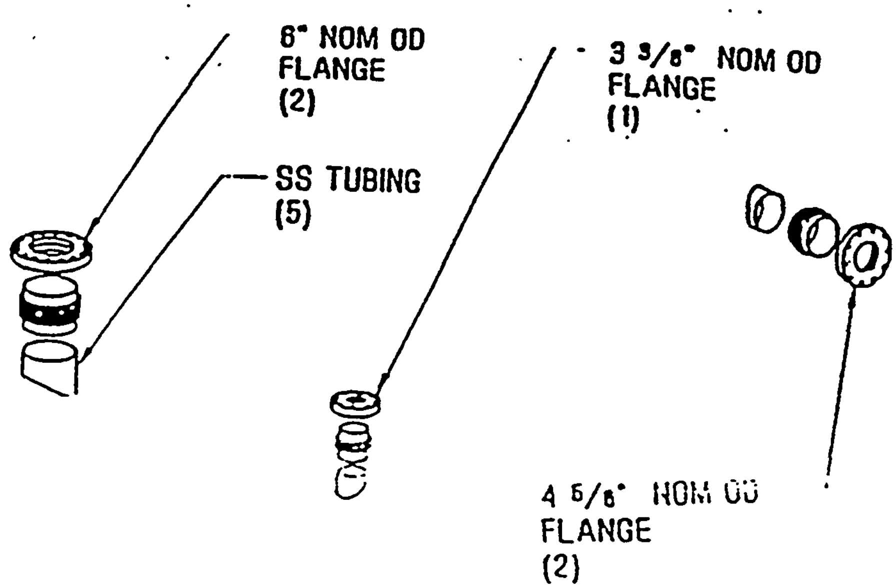
Assemble Parts Into Weld Tooling:
1. RF Power Tube With 6" Flange And Bellows Assembly 2Pcs..
2. Hom Tube With 4.625" Flange And Bellows Assembly 2Pcs..
3. RF Probe Tube With 3.375" Flange And Bellows Assembly 1Pc..

EB Weld:
1. Close Chamber And Pump Down .
2. Weld One (1) Seam On Each RF Power Tube = 25" Of Weld.
3. Weld One (1) Seam On Each HOM Tube = 19" Of Weld.
4. Weld One (1) Seam On RF Probe Tube = 6" Of Weld.
3. Time Required For Rapid Travel.
4. Release Vacuum From Chamber And Open.

Remove Welded Parts From Tooling:
1. RF Power Tube Assemblies 2Pcs..
2. HOM Tube Assemblies 2Pcs..
3. RF Probe Tube Assembly 1Pc..

Inspection:
1. Visual Or X-Ray?
2. Dimensional Check.
3. Leak Check.

Manufacturing Issues
For Discussion



Preparation And Assembly
For Niobium To Niobium
EB Weld #2

Clean Parts For Welding:
1. RF Power Tubes Assemblies 2Pcs..
2. HOM Tubes Assemblies 2Pcs..
3. RF Probe Assembly 1Pc..
4. Cavity End Pipe With Female Inter Lock 1Pc..
5. Cavity End Pipe With Male Inter Lock 1Pc..
6. Cavity 1/2 Cells With Female Inter Lock 4Pcs..
7. Cavty 1/2 Cells With Male Inter Lock 4Pcs..

Assemble Parts Into Weld Tooling:
1. RF Power Tube Assemblies 2Pcs..
2. HOM Tube Assemblies 2Pcs..
3. RF Probe Tube Assembly 1Pc...
4. 1/2 Cells With Femamle Inter Lock 4Pcs..
5. 1/2 Cells With Male Inter Lock 4Pcs..
6. Cavity End Pipe With Female Inter Lock 1Pc...
7. Cavity End Pipe With Male Inter Lock 1Pc..

EB Weld:
1. Close Chamber And Pump Down .
2. Weld Five (5) Minor Dia. On 1/2 Cells = 94" Of Weld.
3. Weld Four (4) Magor Dia. On 1/2 Cells = 195" Of Weld.
4. Weld Two (2) RF Power Tube Assemblies Onto One (1) End Pipe = 26" Of Weld.
5. Weld Two (2) HOM tube Assemblies . One (1) Onto Each End Pipe = 19" Of Weld.
6. Weld One (1) RF Probe Tube Assembly Onto One (1) End Pipe = 7" Of Weld.
7. Time Required For Rapid Travel.
8. Release Vacuum From Chamber And Open.

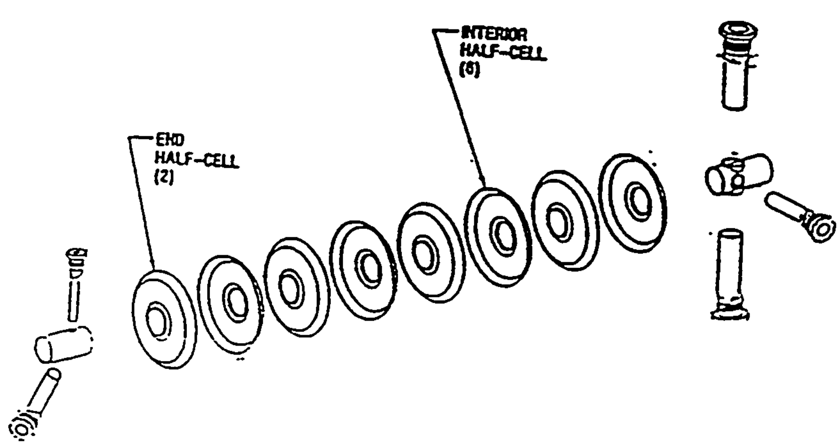
Remove Welded Parts From Tooling:
1. Cavity Assembly Less Stiffeners . 8" End Flanges . And 8" End Flange / Bellows Assemblies.

Inspection:
1. Visual Or X-Ray/
2. Dimensional.
3. Leak Check.

Manufacturing Issues

<u>For Discussion</u>

- Shrinkage Of Niobium.
- Inside Bead Prediction.



Preparation And Assembly
For Niobium To Niobium
EB Weld #3

Clean Parts For Welding:
1. Cavity Assembly Less Stiffeners . 8" End Flanges , And 8" Flange / Bellows Assemblies 1Pcs..
2. Between Cell Stiffeners 1/2 Circles 6Pcs..
3. End Cone Stiffener Segments5Pc..

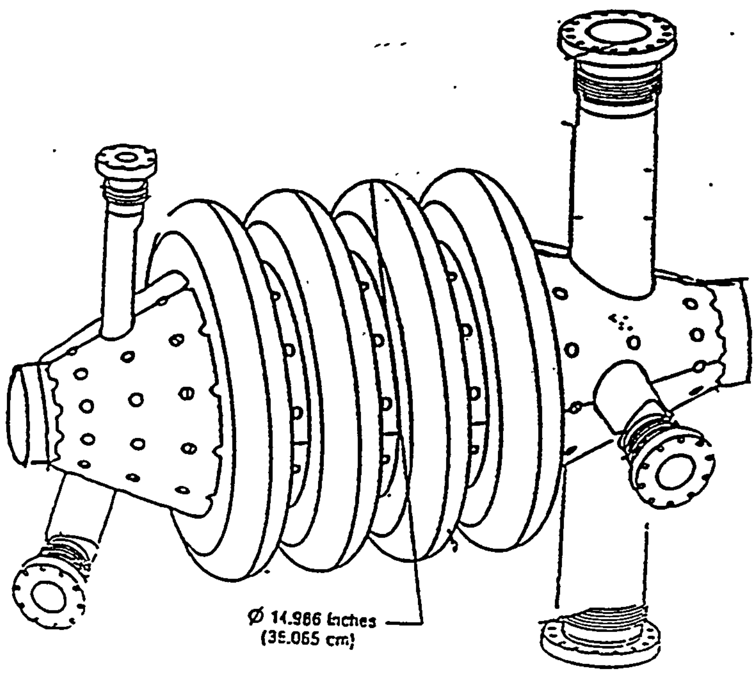
Assemble Parts Into Weld Tooling:
1. Between Cell Stiffeners Onto Cavity Assembly 6Pls..
2. End Cone Three (3) Segments On End Pipe With Two (2) RF Power Tubes And One (1) HOM Tube.
3. End Cone Two (2) Segments On End Pipe With One (1) RF Probe Tube And One (1) HOM Tube.

EB Weld:
1. Close Chamber And Pump Down .
2. Weld Six (6) 1/2 Circle Between Cell Stiffeners = 195" Of Weld.
3. Weld Three (3) End Cone Segments Around One (1) Cavity End Pipe = 58" Of Weld.
4. Weld Two (2) End Cone Segments Around One (1) Cavity End Pipe = 39" Of Weld.
5. Time Required For Rapid Travel.
6. Release Vacuum From Chamber And Open.

Remove Welded Parts From Tooling:
1. Cavity / Stiffener Assembly Less 8" End Flanges And 8" End Flange / Bellows Assemblies.

Inspection:
1. Visual Or X-Ray?
2. Dimensional.

Manufacturing Issues
For Discussion
- Tack,Stitch,Or Continous Weld.
- Penetration Of Weld.
- Clearance Around Pipes.
- Reason For Cutouts On Major And Minor Diameter Of Cones.



Preparation And Assembly
For Stainless Steel To Stainless Steel
Tig Weld #4

Clean Parts For Welding:
1. Cavity / Stiffener Assembly Less 8" End Flanges And 8" Flange / Bellows Assemblies 1Pcs..
2. Cryogen Vessel Central Cyclinder 1/2 Circles With Return Port Hole 1Pc..
3. Cryogen Vessel Central Cyclinder 1/2 Circle With Inlet Port Hole 1Pc..
4. Cryogen Vessel End Cone Segments 5Pcs..
5. Cryogen Vessel End Covers 2Pcs..
6. Cryogen Vessel 11" Flange And Belows Assembly 1Pcs..
7. Cryogen Vessel 8" Flange And Bellows Assembly 1Pcs..
8. Cryogen Vessel Return Tee 1Pc..
9. Cryogen Vessel Inlet Tee 1Pc..

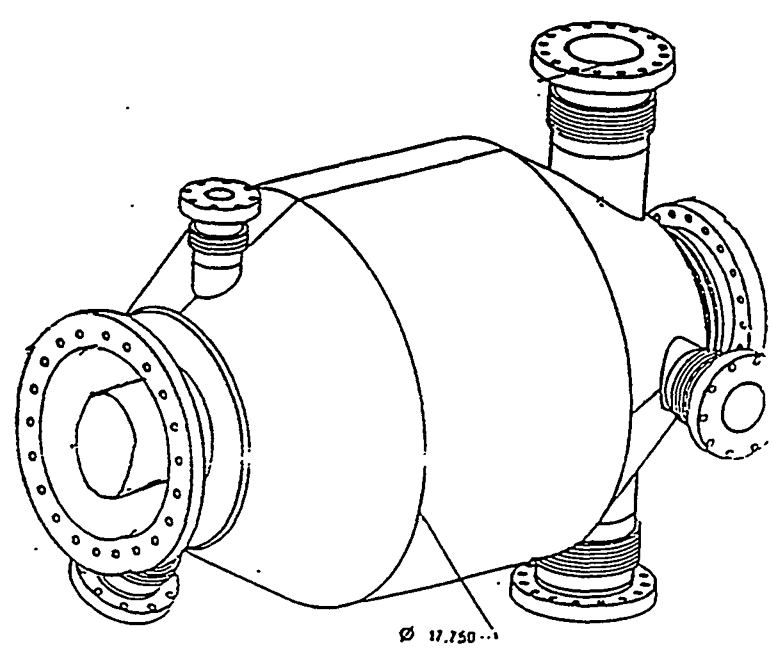
Assemble Parts Into Weld Tooling:
1. Cryogen Vessel Central Cylinder One (1) Return Port And One (1) Inlet Port 1/2 Circcle Around Cavity Assembly.
2. Cryogen Vessel End Cone Three (3) Segments On End With Two (2) RF Power Tubes And One (1) HOM Tube Around Cavity Assembly.
3. Cryogen Vessel End Cone Two (2) Segments On End With One (1) RF Probe Tube And One (1) HOM Tube Around Cavity Assembly.
4. Cryogen Vessel End Covers 2Pcs. One (1) On Each End Around Cavity Assembly.
5. Cryogen Vessel 11" Flange And Bellows Assembly 1Pc. On Cavity End With One (1) RF Probe Tube And One (1) HOM Tube.
6. Cryogen Vessel 8" Flange And Bellows Assembly 1Pc. On Cavity End With Two (2) RF Power Tubes And One (1) HOM Tube.
7. Cryogen Vessel One (1) Return Tee Onto Central Cyclinder.
8. Cryogen Vessel One (1) Inlet Tee Onto Central Cyclinder.

Tig Weld:
1. Tack Weld All Cryogen Vessel Seams Together.
2. Weld All Cryogen Vessel Seams And Around All Pipes = 292" Of Weld.

Remove Welded Parts From Tooling:
1. Cavity With Cryogen Vessel Assembly Less 8" Cavity End Flanges And 8" Cavity Flange / Bellows Assemblies.

Inspection:
1. Visual Or X-Ray?
2. Dimensional Check.
3. Leak Check.

Manufacturing Issues
For Discussion



Preparation And Assembly
For Stainless Steel To Niobium
EB Weld #5

Clean Parts For Welding:
1. 8" Cavity End Flange 2Pcs..
2. Cavity With Cryogen Vessel Less 8" Cavity End Flanges And 8" Cavity Flange / Bellows. Assemblies 1Pc..

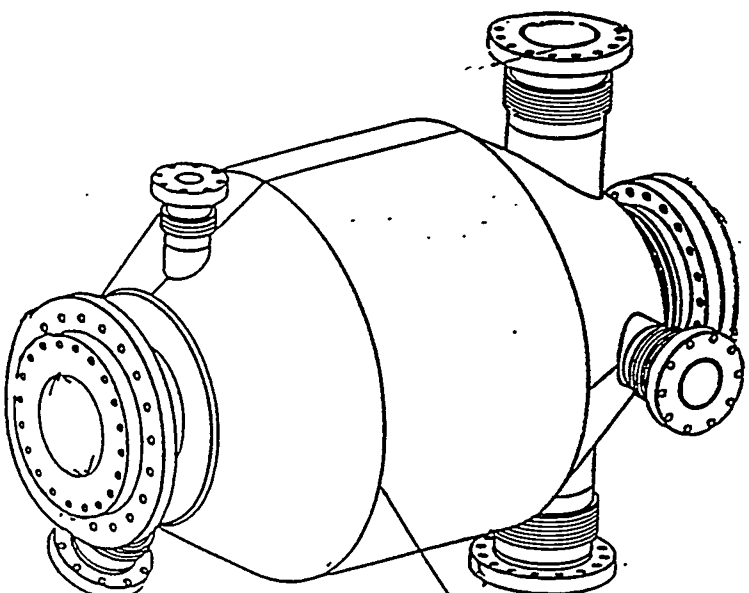
Assemble Parts Into Weld Tooling:
1. Cavity With Cryogen Vessel And Two (2) End Flanges One (1) On Each End.

EB Weld:
1. Close Chamber And Pump Down .
2. Weld Two (2) Cavity End Flanges One On Each Cavity End Pipe On Inside Diameter = 37" Of Weld.
3. Time Required For Rapid Travel.
4. Release Vacuum From Chamber And Open.

Remove Welded Parts From Tooling:
1. Cavity With Cryogen Vessel Less 8" Cavity Flange / Bellows Assemblies.

Inspection:
1. Visual Or X-Ray?
2. Dimensional Check.
3. Leak Check.

Manufacturing Issues
For Discussion



Preparation And Assembly
For Stainless Steel To Stainless Steel
Tig Weld #6

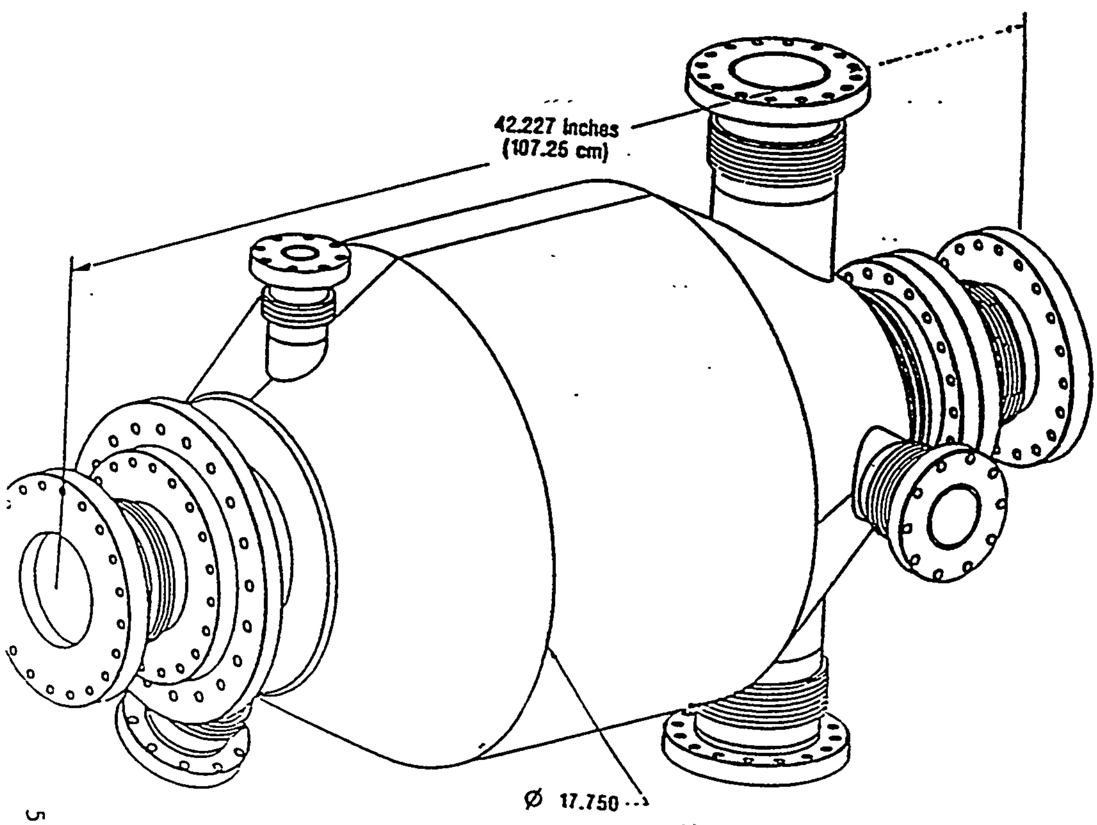
Clean Parts For Welding:
1. Cavity With Cryogen Vessel Less 8" Cavity Flange / Bellows Assemblies.
2. 8" Cavity Flange And Bellows Assemblies 2Pcs..

Assemble Parts Into Weld Tooling:
1. Cavity With Cryogen Vessel And Two (2) 8" Cavity Flange And Bellows Assemblies One (1) Each End.

Tig Weld:
1. Weld Two (2) Flange / Bellows Assemblies Onto Cavity End Flanges One (1) On Each End = 38" Of Weld.

Remove Welded Parts From Tooling:
1. Completed Cavity With Cryogen Vessel Assembly.

Inspection:
1. Visual Or X-Ray?
2. Dimensional Check.
3. Leak Check.



Cavity And Cryogen Vessel Assembly Preparation Prior To Installation Into Cryomodule

1. Degreasing Cleaning Process.
2. Drying (Purge With Heated Dry Nitrogen).
3. Cap Off Inlet And Return Tee's On Cryogen Vessel.
4. Clean Inside Surfaces Of Cavity With Buffered Chemical Polishing.
5. Rinse With Ultra Pure Water.
6. Ultrasonic Agitation , Twofold Rinsing With Reagent Grade Methanol Till Class 100 Has Been Achieved.
7. Drying.(Purg With Heated Dry Nitrogen Filtered To Class 100).
8. Cap Off Two (2) Cavity End Flanges , Two (2) RF Power Port Flanges , Two (2) HOM Port Flanges , And One (1) RF Probe Port Flange.
9. Evacuate Cavity And Seal.
10. Clean Outside Surface Of Cavity And Cryogen Vessel Assembly To Level 100.
11. Double Bag Cavity And Cryogen Vessel Assembly For Storage And / Or Shipment To Assembly Facility.

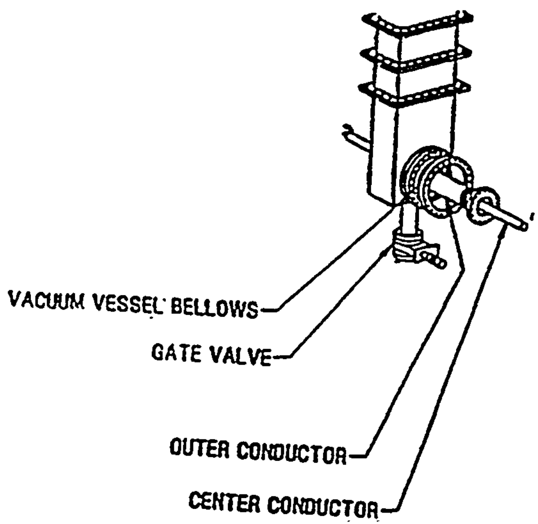
Manufacturing Issues
For Discussion

- Effect Of Buffered Chemical Polishing On Conflat Flanges.

Purchased Parts Required
For
RF Drive Line Assembly

1. RF Center Conductor Drive Shaft.
2. RF Center Conductor 1PC..
3. RF Drive Line / Cavity Vacuum Valve 1Pc..
4. Vacuum Vessel Flange / Bellows Assembly 1Pc..
5. RF Wave Guide Window Assembly 1Pc..
6. RF Wave Guide End With Vacuum Vessel Bellows Flange . Outer Conductor Bellows / Flange Tube Assembly ,
   Center Conductor Flange . And RF Drive Line / Cavity Vacuum Port 1Pc..

Manufacturing Issues
<u>For Disucssion</u>



Cleaning And Assembly Of RF Drive Line Assembly In A Class 100 Clean Room

Clean Parts To Class 100 Using Ultrasonic Agitation. Twofold Rinsing With Reagent Grade Methanol:

1. RF Center Conductor Drive Shaft 1Pc..
2. RF Center Conductor 1PC..
4. RF Drive Line / Cavity Vacuum Valve 1Pc..
5. RF Wave Guide Window Assembly 1Pc..
6. RF Wave Guidr End Assembly 1pc..
7. VacuumVessel Flange / Bellows Asseembly 1Pc..

Assembly In Class 100 Clean Room:

1. Install Vacuum Vessel Flange / Bellows Assembly Onto RF Wave Guide End Assembly.
2. Install RF Drive Line / Cavity Vacuum Valve Onto RF Wave Guide End Assembly.
3. Install RF Wave Guide Window Assembly Onto RF Wave Guide End Assembly.
4. Install RF Center Conductor Into RF Drive Shaft Assembly.
5. Install RF Drive Shaft Assembly With RF Center Conductor Into RF Wave Guide End Assembly.

Testing And Inspection:

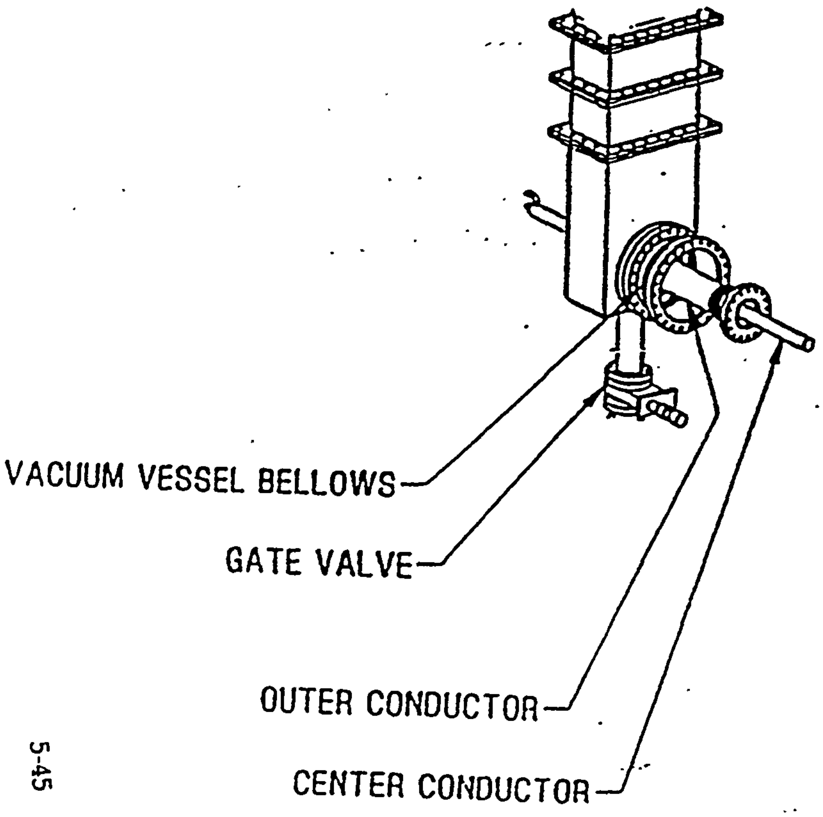
1. Install Temporary Seal / Storage Flange Test Assembly OntoVacuum Vessel Flange / Bellows And Outer Conductor Bellows / Flange Tube Assembly.
2. Leak Check.
3. Check Assembly For Correct Hardware And Installtion..

Storage:

1. Evacuate RF Drive Line Assembly And Seal.
2. Double Bag RF Drive Line Assembly For Storage Untill Installation Into Cryomodule.

Manufacturing Issues

For Discussion

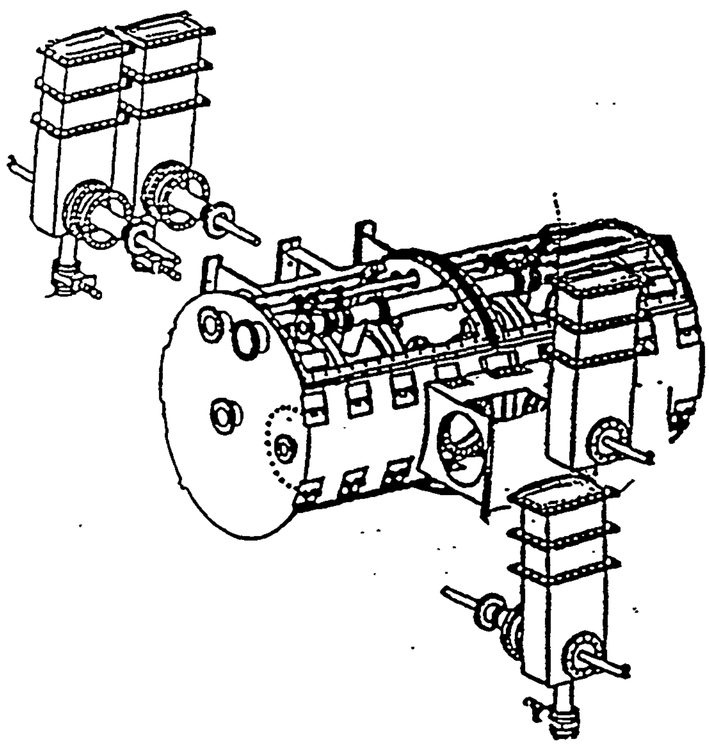


Purchased Parts And Precleaned / Preassemblied Parts Required For Cryomodule Subassembly

Additional Parts:
1. Coolant Shield Ring Manifolds 4PCS..
2. Support Arm (5 Per. Cavity) 10Pcs..
3. HOM Wave Guide Assembly For RF Power End Of Cavity (1 Per. Cavity) 2Pcs..
4. HOM Wave Guide Assembly For RF Probe End Of Cavity (1 Per. Cavity) 2Pcs.
5. HOM Wave Guide Window Assembly 4Pcs..
6. RF Probe Assembly (1 Per. Cavity) 2Pcs..
7. Cryomodule Main Body Structure Less Support Stand . Removable Staves . And Skins 1PC..

Precleaned And Assemblied Parts:
1. Cavity And Cryogen Vessl Assembly 2Pcs..
2. RF Drive Line Assembly 4Pcs..

Manufacturing Issues
For Discussion



Cleaning And Assembly Of Cryomodule Subassembly In A Class 100 Clean Room

Clean Parts To Class 100 Using Ultrasonic Agitation ,.Twofold Rinsing With Reagent Grade Methanol And Dry By Purging With Heated Dry Nitrogen Filtered To Class 100:

1. Coolant Shield Ring Manifolds 4PCS..
2. Support Arm (5 Per. Cavity) 10Pcs..
3. HOM Wave Guide Assembly For RF Power End Of Cavity (1 Per. Cavity) 2Pcs..
4. HOM Wave Guide Assembly For RF Probe End Of Cavity (1 Per. Cavity) 2Pcs.
5. HOM Wave Guide Window Assembly 4Pcs..
6. RF Probe Assembly (1 Per. Cavity) 2Pcs..
7. Cryomodule Main Body Structure Less Support Stand . Removable Staves . And Skins 1Pc..

Storage Of Parts Prior To Assembly:

1. Double Bag All Parts For Storage Until Installation Into Cryomodule Subassembly.

Assembly In Class 100 Clean Room:

1. Install Cryomodule Main Body Structure Into Assembly Tooling.
2. Release Vacuum From One (1) Cavity And Cryogen Vessel Assembly.
3. Place One (1) Coolant Shield Ring Manifold Around Each End Of Cavity And Cryogen Vessel Assembly Two (2) Coolant Shield Ring Manifolds Required.
4. Remove Flange Caps From Both Cavity End Flanges.
5. Install Cavity And Cryogen Vessel Assembly Onto Beam Tube Interface Nipples In One (1) Cell Of The Cryomodule Main Structures Two (2) Cells And Attach Five (5) Support Arms.
6. Install Flange Cap Onto Beam Tube Interface Nipple (Outboard Flange).
7. (REPEAT STEPS 2 Thru. 6) For The Cryomodule Main Structures Second Cell And Adjust Beam Line.
8. Remove Flange Cap From HOM Port On RF Power End Of Cavity And Cryogen Vessel Assembly.
9. Install One (1) HOM Wave Guide Assembly For RF Power End Of Cavity Between RF Power Flange And HOM Interface Nipple In One (1) Cell Of The Cryomodule Main Structures Two (2) Cells.
10. Install HOM Wave Guide Window Assembly Onto HOM Interface Nipple.
11. Install HOM Flange Cap Onto HOM Wave Guide Window Assembly.
12. (REPEAT STEPS 8 Thru. 11) For HOM Port On RF Probe End Of Cavity And Cryogen Vessel Assembly.
13. Remove RF Probe Flange Cap.
14. Install RF Probe Onto Flange.
15. (REPEAT STEPS 8 Thru. 14) For The Cryomodule Main Structures Second Cell.
16. Install Temporary Support Tooling Onto RF Drive Line Assembly.
17. Remove One (1) RF Power Flange Cap.
18. Insert One (1) RF Drive Line Assembly Through Cryomodule Main Structure RF Coupler Vacuum Vessel Flange And Center Conductor Into RF Power Port.
19. Secure Temporary Support Tooling To Cryomodule Main Structure.
20. Install Hardware Into Outer Conductor Bellows And RF Power Flange Interface.
21. Install Hardware Into RF Coupler Vacuum Vessel Bellows And Cryomodule Main Structure RF Coupler Vacuum Vessel Flange.
22. (REPEAT STEPS 16 Thru. 21) For Remaining Three (3) RF Drive Line Assemblies.

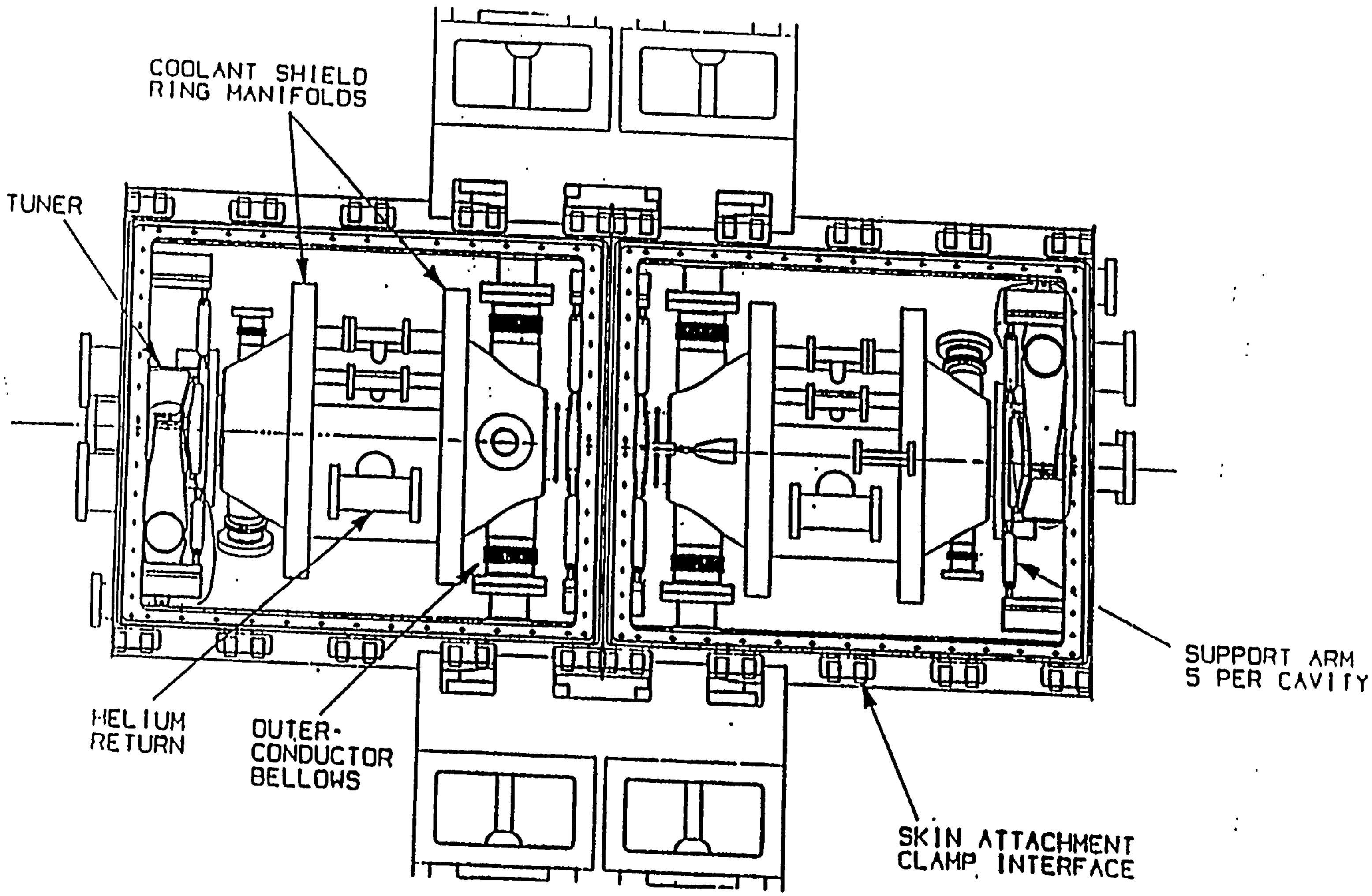
Testing And Inspection:

1. Inspect For Proper Assembly Of Cryomodule Subassembly.
1. Check Beam Line Adjustment Of Cryomodule Subassembly.
2. Leak Check Cryomodule Subassembly.

Storage Or Further Assembly:

1. Evacuate Cavity Assembly And Seal.
2. Double Bag Cryomodule Subassembly For Storage Until Final Assembly.

(NOTE THIS COMPLETES CLASS 100 CLEAN ROOM OPERATIONS)


COOLANT SHIELD
RING MANIFOLDS
TUNER
HELIUM
RETURN
OUTER-
CONDUCTOR
BELLOWS
SUPPORT ARM
5 PER CAVITY
SKIN ATTACHMENT
CLAMP INTERFACE

Purchased Parts Required
For
Cryomodule Final Assembly

1. Cavity And Cryogen Vessel EMI Blanket Assembly 2Pcs..
2. Cryomodule Skin EMI Blanket Assembly 4Pcs..
3. Cryomodule Main Structure Side EMI Blanket Assembly 4Pcs..
4. Cryomodule Main Structure End Plate EMI Blanket Assembly 2Pcs..
5. Skin Staves 4Pc...
6. Side Staves Assembly 4Pcs..
7. End Plate Sraves Assembly 2Pcs..
8. Cryomodule Skin Assembly 4Pc..
9. RF Drive Mechanism Interface Plate 2Pc..
10. Tuner Drive Mechanism Interface Plate 2Pcs..
11. Drive Mechanism 6Pcs..
12. RF Drive Line / Cavity Vacuum Pumps 4Pcs..
13. RF Feed Line Bellows Assembly 4Pcs..
14. Flexure Tuner Assembly 2Pcs..
15. Magnetostrictive Actuator . Bellows . And Tuner Drive Link Assembly 2Pcs..
16. Cryogen Vessel Helium Return Cross-Over Bellows / Tube Assembly 1Pc...
17. Cryogen Vessel Helium Return Bellows / Tube Assembly 1Pc..
18. Cryogen Vessel Helium Return Flange Cap 1Pc..
19. Cryogen Vessel Helium Feed Cross-Over Bellows / Tube Assembly 1Pc...
20. Cryogen Vessel Helium Feed Bellows / Tube Assembly 1Pc..
21. Cryogen Vessel Helium Feed Flange Cap 1Pc...
22. Coolant Shield Ring Manifold Return 90Deg. Cross-Over Tube Assembly 1Pc..
23. Coolant Shield Ring Manifold Return Tube Assembly 1Pc..
24. Coolant Shield Ring Manifold Return Tee Fittings 3Pcs..
25. Coolant Shield Ring Manifold Feed 90Deg. Cross-over Tube Assembly 1Pc..
26. Coolant Shield Ring Manifold Feed Tube Assembly 1Pc..
27. Coolant Shield Ring Manifold Feed Tee Fittings 3Pcs..
28. Cryomodule Skin Seals 4Pcs..
29. Cryomodule Support Stand 1Pc...

Cleaning Parts Required For Cryomodule Final Assembly In A Class 100,000 Clean Room

Clean Parts To Class 100.000 By Rinsing Wuth Reagent Grade Methanol And Dry By Purging With Heated Dry Nitrogen Filtered To Class 100.000:

1. Cavity And Cryogen Vessel EMI Blanket Assembly 2Pcs..
2. Cryomodule Skin EMI Blanket Assembly 4Pcs..
3. Cryomodule Main Structure Side EMI Blanket Assembly 4Pcs..
4. Cryomodule Main Structure End Plate EMI Blanket Assembly 2Pcs..
5. Skin Staves 4Pc...
6. Side Staves Assembly 4Pcs..
7. End Plate Sraves Assembly 2Pcs..
8. Cryomodule Skin Assembly 4Pc..
9. RF Drive Mechanism Interface Plate 2Pc..
10. Tuner Drive Mechanism Interface Plate 2Pcs..
11. Drive Mechanism 6Pcs..
12. RF Drive Line / Cavity Vacuum Pumps 4Pcs..
13. RF Feed Line Bellows Assembly 4Pcs..
14. Flexure Tuner Assembly 2Pcs..
15. Magnetostrictive Actuator. Bellows. And Tuner Drive Link Assembly 2Pcs..
16. Cryogen Vessel Helium Return Cross-Over Bellows / Tube Assembly 1Pc...
17. Cryogen Vessel Helium Return Bellows / Tube Assembly 1Pc..
18. Cryogen Vessel Helium Return Flange Cap 1Pc..
19. Cryogen Vessel Helium Feed Cross-Over Bellows / Tube Assembly 1Pc...
20. Cryogen Vessel Helium Feed Bellows / Tube Assembly 1Pc..
21. Cryogen Vessel Helium Feed Flange Cap 1Pc...
22. Coolant Shield Ring Manifold Return 90Deg. Cross-Over Tube Assembly 1Pc..
23. Coolant Shield Ring Manifold Return Tube Assembly 1Pc..
24. Coolant Shield Ring Manifold Return Tee Fittings 3Pcs..
25. Coolant Shield Ring Manifold Feed 90Deg. Cross-over Tube Assembly 1Pc..
26. Coolant Shield Ring Manifold Feed Tube Assembly 1Pc..
27. Coolant Shield Ring Manifold Feed Tee Fittings 3Pcs..
28. Cryomodule Skin Seals 4Pcs..
29. Cryomodule Support Stand 1Pc..

Storage Or Further Assembly:

1. Double Bag Parts For Storage Until Installation Into Cryomodule.

Cryomodule Final Assembly
In A
Class 100,000 Clean Room

Assembly Stage #1:

1. Install Cryomodule Subassembly Into Assembly Tooling.
2. Rap Each Cavity And Cryogen Vessel Assembly In One (1) EMI Blanket Assembly 2 Assemblies Required.
3. Install One (1) End Plate EMI Blanket Assembly On Each End Of Cryomodule 2 Assemblies Required.
4. Install One (1) End Plate Stave Assembly Over Each Of The End Plate EMI Blankets 2 Assemblies Required.
5. Install One (1) Side EMI Blanket Assembly On Each Of The Cryomodule Sides 4 Assemblies Required.
6. Install One (1) Side Stave Assembly Over Each Of The Side EMI Blankets 4 Assemblies Required.

Inspection:

1. Inspect For Proper Installation Of EMI Blankets And Staves.

Assembly Stage #2:

7. Install One (1) Flexure Tuner Assembly Onto Each Cavity / Cryogen Vessel Assembly And Cryomodule End Plate 2 Assemblies Required.
8. Install One (1) Tuner Drive Mechansim Interface Plate On Each End Of The Cryomodule 2Pcs..
9. Assemble One (1) Magnetostrictive Actuator, Bellows, And Tuner Drive Link IntoOne (1) Drive Mechanism Two (2) Of These Assemblies Are Required.
10. Insert One (1) Of Step #9's Assemblies Through Tuner Drive Mechanism Iterface Plate Secure With Mounting Hardware, Adjust Tuner Drive Link, And Atach To Flexure Tuner Assembly.
11. (REPEAT STEP #10) For Other Ends Of Cryomodule.

Test And Inspection:

1. Inspect For Proper Installation Of The Two (2) Flexure Tuner Assemblies.
2. Test Operational Performance For Each Of The Two (2)Tuner Drive Mechanisms .
3. Check Each Of The Two (2) Flexure Tuner Assemblies For Correct Adjustment.

Assembly Stage #3:

12. Install One (1) RF Drive Mechanism Interface Plate Onto Each Of The Two (2) Sets Of RF Coupler Brakets On Each Side Of The Cryomodule.
13. Install One (1) Drive Mechanism Over Each Of The Four (4) Drive Shafts And Secure To RF Drive Mechanism Interface Plate With Hardware.
14. Attach Drive Shaft To Drive Mechanism And Adjust Center Conductor On Each Of The Four (4) RF Coupler Assemblies.
15. Connect RF Probe Wires To Electrical Interface Connector In Cryomodules Main Stucture Two (2) RF Probe Connection Required.

Test And Inspection:

1. Inspect For Proper Installation Of The Four (4) RF Couplers Center Conductor Adjustment Mechanisms.
2. Test Operational Performance For Each Of The Four (4) RF Coupler Center Conductor Adjustment Mechanisms.
3. Check The Adjustment On Each Of The Four (4) Center Conductors.
4. Inspect Electrical Connections Of The Two (2) RF Probes For Proper Assembly To The Interface Connectors.
5. Test Electrical Performance Of The Two (2) RF Probes.

Assembly Stage #4:

16. Install One (1) Return Tee And One (1) Feed Tee Between The Two (2) Coolant Shield Ring Manifold Assembled Around Each Of The Two (2) Cavity And Cryogen Vessel Assemblies.
17. Install One (1) Return Tee Onto Return Tee Of Coolant Shield Ring Manifold Assembly On Return Side Of Cryomodule.
18. Install One (1) Feed Tee Onto Feed Tee Of Coolant Shield Ring Manifold Assembly On Feed Side Of Cryomodule.

Cryomodule Final Assembly Continued

Assembly Stage #4:

19. Install One (1) Return 90Deg. Cross-Over Tube Assembly And One (1) Feed 90Deg. Cross-Over Tube Assembly Between The Two (2) Coolant Shield Ring Manifolds.
20. Install One (1) Return Tube Assembly Between Coolant Shield Ring Manifold Tee And Coolant Shield Ring Helium Return Interface Nipple Located In Cryomodules End Plate.
21. (REPEAT STEP #20) For One (1) Feed Tube Assembly.

Test And Inspection:

1. Inspect Coolant Shield Ring System For Proper Installation.
2. Leak Check.
3. Purge Coolant Shield Ring System With Dry Nitrogen And Seal For Shipment.

Assembly Stage #5:

22. Install One (1) Cryogen Vessel Helium Return Cross-Over Bellows / Tube Assembly Between The Two (2) Cavity And Cryogen Vessel Assemblies.
23. Install One (1) Cryogen Vessel Helium Return Bellows / Tube Assembly Between Cavity And Cryogen Vessel Assembly And Helium Return Interface Nipple Located In Cryomodules End Plate.
24. Install One (1) Cryogen Vessel Helium Return Flange Cap.
25. (REPEAT STEPS 22 Thru. 24) For Cryogen Vessel Helium Feed Assembly.

Test And Inspection:

1. Inspect Cryogen Vessel Helium System For Proper Installation.
2. Leak Check.
3. Purg Cryogen Vessel Helium System With Dry Nitrogen And Seal For Shipment.

Assembly Stage #6:

26. Install One (1) Skin Stave Into Cryomdule, One (1) Skin EMI Blanket Assembly Onto Skin Stave, One (1) Skin Seal Into Cryomodule, And Attach One (1) Skin Assembly To Cryomodule.
27. (REPEAT STEP 26) For Each Of The Four (4) Cryomodule Openings.

Test And Inspection:

1. Inspect For Proper Assembly And Installation Of Skins.
2. Leak Check.
3. Evacuate And Seal For Shipment.

Assembly Stage #7:

28. Install One (1) RF Drive Line / Cavity Vacuum Pump Onto Each Of The Four (4) RF Drive Line / Cavity Vacuum Valves.

Test And Inspection:

1. Inspect For Proper Installation On Each Of The Four (4) RF Drive Line / Cavity Vacuum Pumps.
2. Test The Operational Performance On Each Of The Four (4) RF Drive Line / Cavity Vacuum Pumps.
3. Leak Check Each Pump During Their Operational Performance Test.

Assembly Stage #8:

29. Remove Cryomodule From Assembly Tooling.
30. Insert Cryomodule Into Supprt Stand And Secure With Hardware.
31. Install One (1) Quadrupole Doublet Assembly Into Support Stand, Attach To Cryomodule, And Adjust Beam Line.

Test And Inspection:

1. Inspect For Proper Installation Of Cryomodule Assembly Into Support Stand.

Cryomodule Final Assembly Continued

Test And Inspection :

2. Inspect For Proper Installation Of Quadrupole Doublet Assembly .
3. Check Beam Line Adjustments.
4. Leak Check Quadrupole Doublet Assembly.
5. Evacuate And Seal For Shippment

Assembly Stage #9:

32. Install Shipping Caps On Each Of The Four (4) RF Windows Assemblies.
33. Bag For Shipment And Remove From Class 100,000 Clean Room.

Cryomodule Preparation
Prior
To Shipment

1. Kit One (1) RF Feed Line Bellows Assemblies With Mounting Hardware.
2. Package Into Shipping Crate One (1) Cryomodule Assembly And Four (4) RF Feed Line Bellows Kits.
3. Seal Up Shipping Crate For Shipment.
4. Place In Holding Area Or Ship To Site.

5.1.3 RF Power Stations

Assumptions for Scheduling of Production RF Stations

In order to provide a schedule for the production of the RF Stations a number of assumptions were made. The first of these relates to the possibility of using the HOMIOT as the output tube for the 700 MHz stations. Because the decision date for the HOMIOT vs klystron selection appears as late as it does, the assumption is made that the preliminary design of both klystron and HOMIOT approach will be started simultaneously, with a down select made after the tube is chosen. At that time the effort on the approach not selected can be curtailed. And alternate to this approach is to force an earlier selection of the output tube. Indications have been that the HOMIOT development could proceed more rapidly, but the assurances gained by accumulating operating hours is certainly essential to make the selection. With the exception of the HOMIOT, there are multiple vendors on virtually all of the major subassemblies and components for the RF Stations. This fact not only ensures competition but is going to be necessary to meet the high rate production required for the RF equipment. The model utilizes a learning curve based on the total quantities required. Splitting orders between vendors will make the quantities smaller but the competition should allow even greater price breaks.

5.1.3 RF Power Stations (continued)

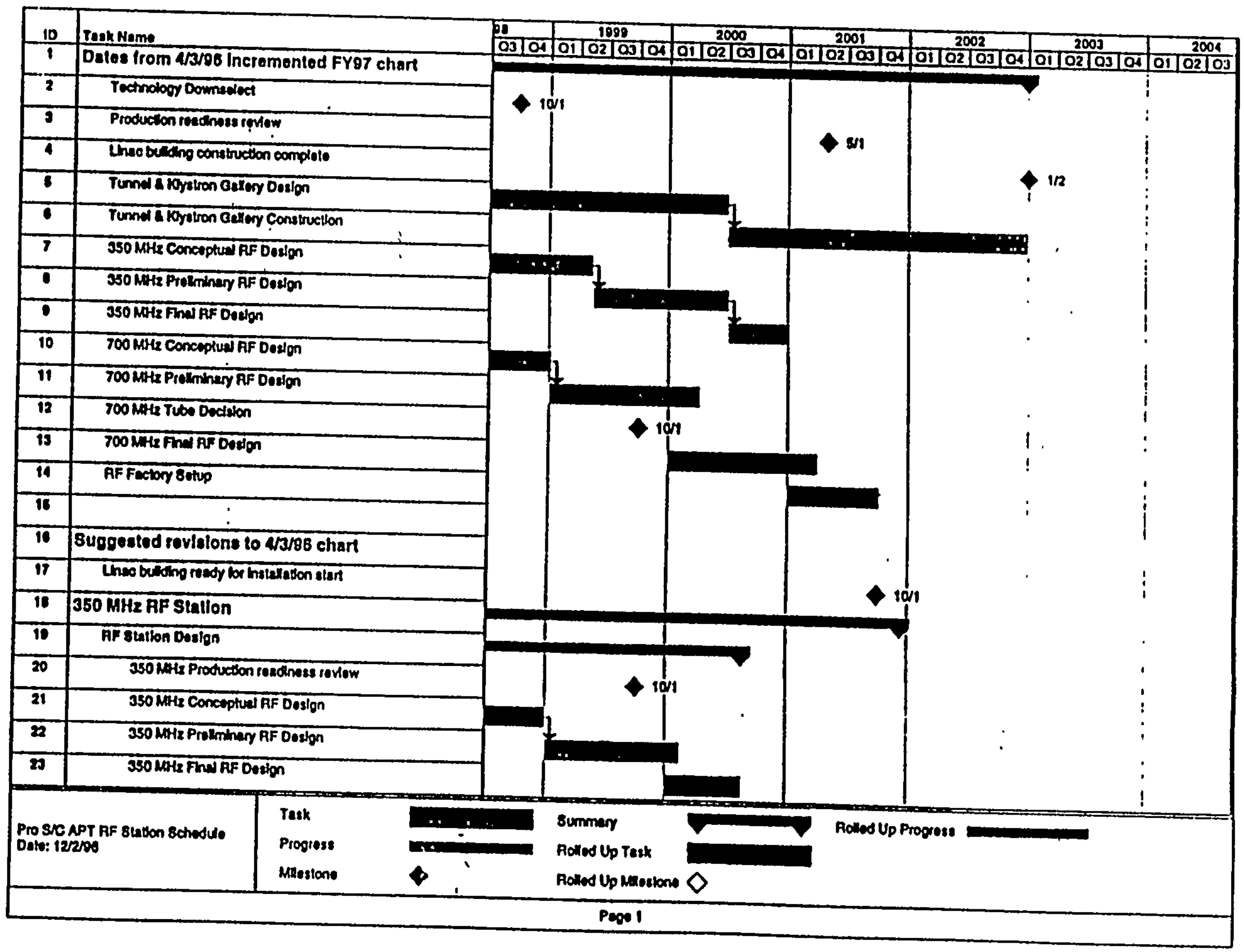
Integration of all of the 350 MHz and first seven 700 MHz RF stations is assumed to be done at contractors facility to ensure that the interfaces and production drawings, tolerances, and interfaces are proven. After that time, because of the extensive use of tested assemblies at the subcontractor facilities, the remaining RF Stations can be integrated directly at the final site. The schedule shows that the production of the RF equipment should start relatively early to meet the proposed end dates. However, the klystron gallery completion schedule shows 12/31/02, creating a need to store huge amounts of equipment for over a year. What is suggested is that the installation of the RF equipment starts on 10/1/01, prior to the completion of the klystron gallery. Since this is an extremely long building, it is assumed that there would be progress from the injector end to the target end and that the installation could start as the first parts of the building are available. Even without operating power to run the equipment, significant schedule advantage can be gained by starting the installation early.

There are assumptions made for the definition of the outputs of the program phases. It is assumed that the Preliminary Design phase results in the generation of manufacturing drawings adequate to do high volume production planning. Limited manufacturing of the key assemblies would be done during the end of the preliminary design phase to verify manufacturability prior to start of full production. Final design will entail changes to the manufacturing drawings to minimize any impediments to successful high volume production

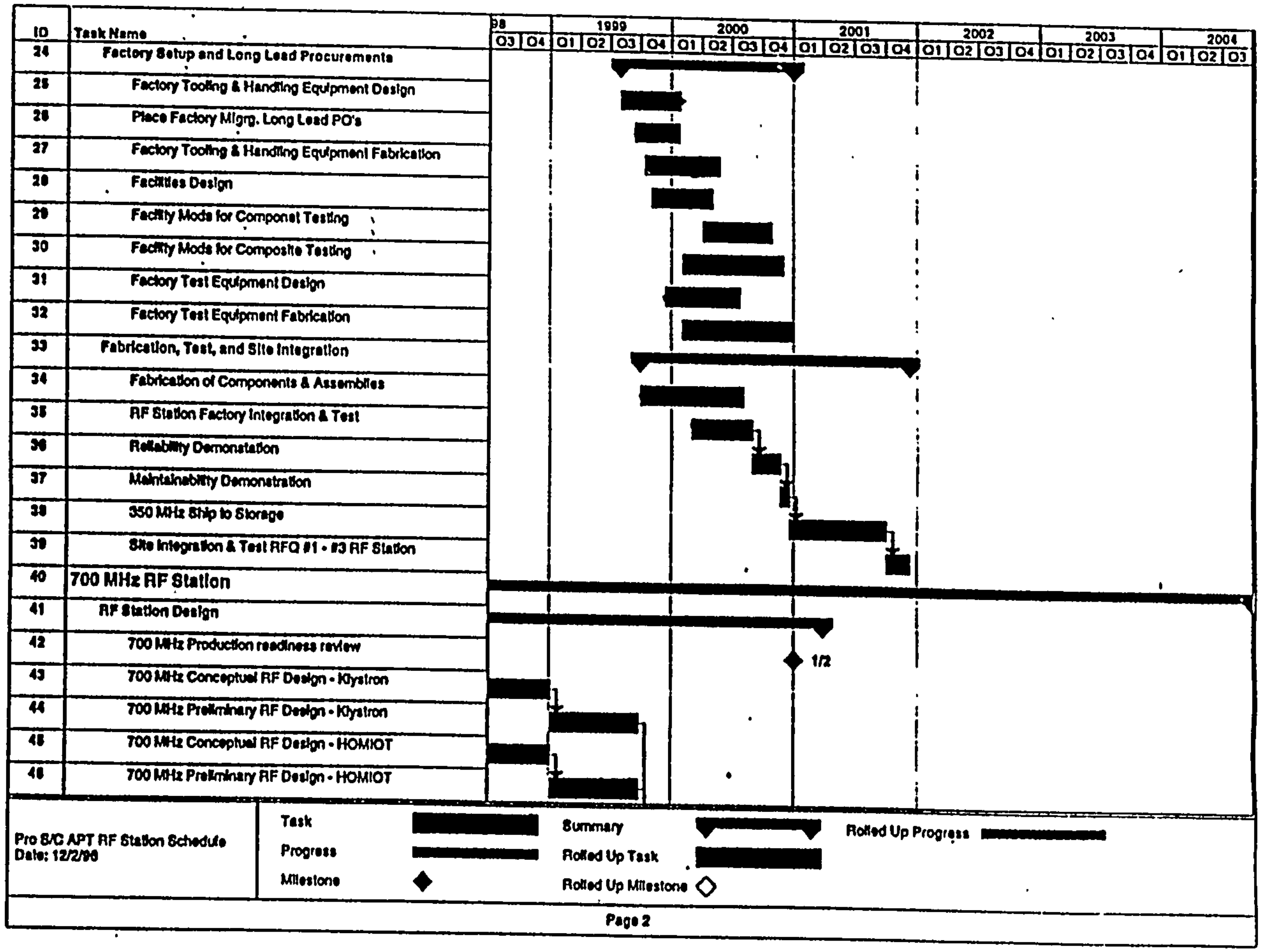
Assumptions for Scheduling of Production RF Stations

- Start preliminary design activity of 700 MHz klystron & HOMIOT RF Station configurations and downselect after tube selection is made or expedite the tube effort to make the downselect earlier
- Large percentage of the components can be bid competitively
- Costs reflect learning curves for high volume production
- Integrate RF Stations directly at site after all 350 MHz and first seven 700 MHz RF stations are done at contractors facility
- Preliminary design phase assumes that the design has progressed to the point where manufacturing drawings exist and planning for the construction phase can start
- Manufacture small quantity of key assemblies during the end of the preliminary design phase to verify manufacturability prior to start of full production
- Final design will update the manufacturing drawings to ensure producability
- Start installation prior to final completion of klystron gallery (10/1/2001) to relieve schedule concerns and minimize the need for large storage space for production equipment

APT RF Station Schedule

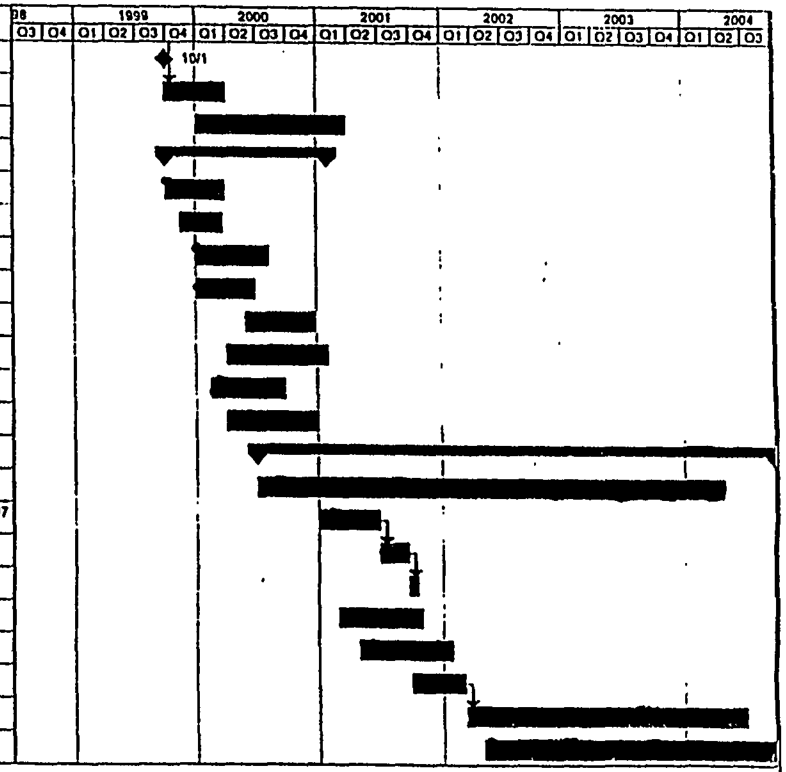


APT RF Station Schedule



APT RF Station Schedule

ID	Task Name
47	700 MHz Tube Decision
48	Downselected 700 MHz Preliminary Design
49	700 MHz Final RF Design
50	Factory Setup and Long Lead Procurements
51	Factory Tooling & Handling Equipment Design
52	Place Factory Mfgrg. Long Lead PO's
53	Factory Tooling & Handling Equipment Fabrication
54	Facilities Design
55	Facility Mods for Componet Testing
56	Facility Mods for Composite Testing
57	Factory Test Equipment Design
58	Factory Test Equipment Fabrication
59	Fabrication, Test, and Site Integration
60	Fabrication of 700 MHz Components & Assemblies
61	700 MHz RF Station Factory Integration & Test #1 thru #7
62	Reliability Demonstration
63	Maintainability Demonstration
64	700 MHz RF Station #1 thru #7 Ship to Storage
65	700 MHz Components & Assemblies Ship to Storage
66	700 MHz RF Station Site Integration & Test #1 thru #7
67	700 MHz RF Station Site Integration #8 thru #234
68	700 MHz RF Station Site Test #8 thru #234



Pro S/C APT RF Station Schedule
Date: 12/2/98

Task | Summary | Rolled Up Progress
Progress | Rolled Up Task
Milestone | Rolled Up Milestone

Page 3

Accelerator Production of Tritium

5.2 Evaluations of Integrated Production Schedules

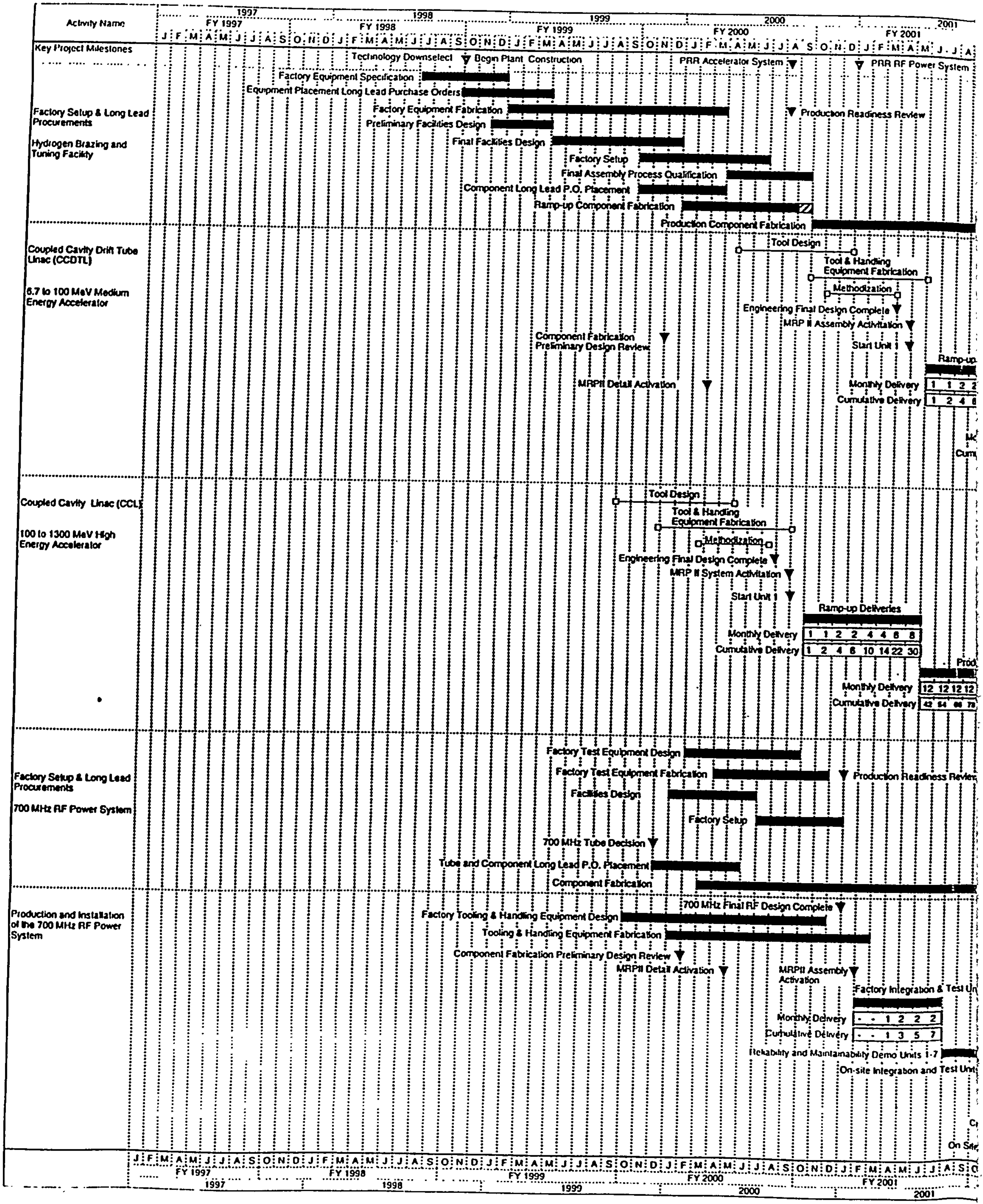
Typical Flow Plans and Cycles Plans were developed for rate production structures on both normal conducting and superconducting accelerators. "Grass Roots" estimates of conceptual design data provided the basis for establishing production work station flows for a planned two (2) shift operation on a five (5) day work week.

Starting with major milestones defined in LANL Integrated Accelerator Schedule of 4/96, A preliminary schedule assessment was constructed as shown in Section 5.2.1 (page 5-62) and section 5.2.2 (page 5-63 & 5-64).

Phased Preliminary Design Reviews (PDR's) were scheduled prior to industries placing longlead purchase orders for components. Production Readiness Reviews (PRR's) at the industry fabrication facility were planned to ensure assembly qualification. An industry ramp-up phase was scheduled to proceed a production phase where peak deliveries are attained. Installation and testing of accelerator and RF Power modules were planned to be started at SRL prior to completion of tunnel and klystron gallery construction (phased start-up).

Section 5.2.1 Preliminary Schedu

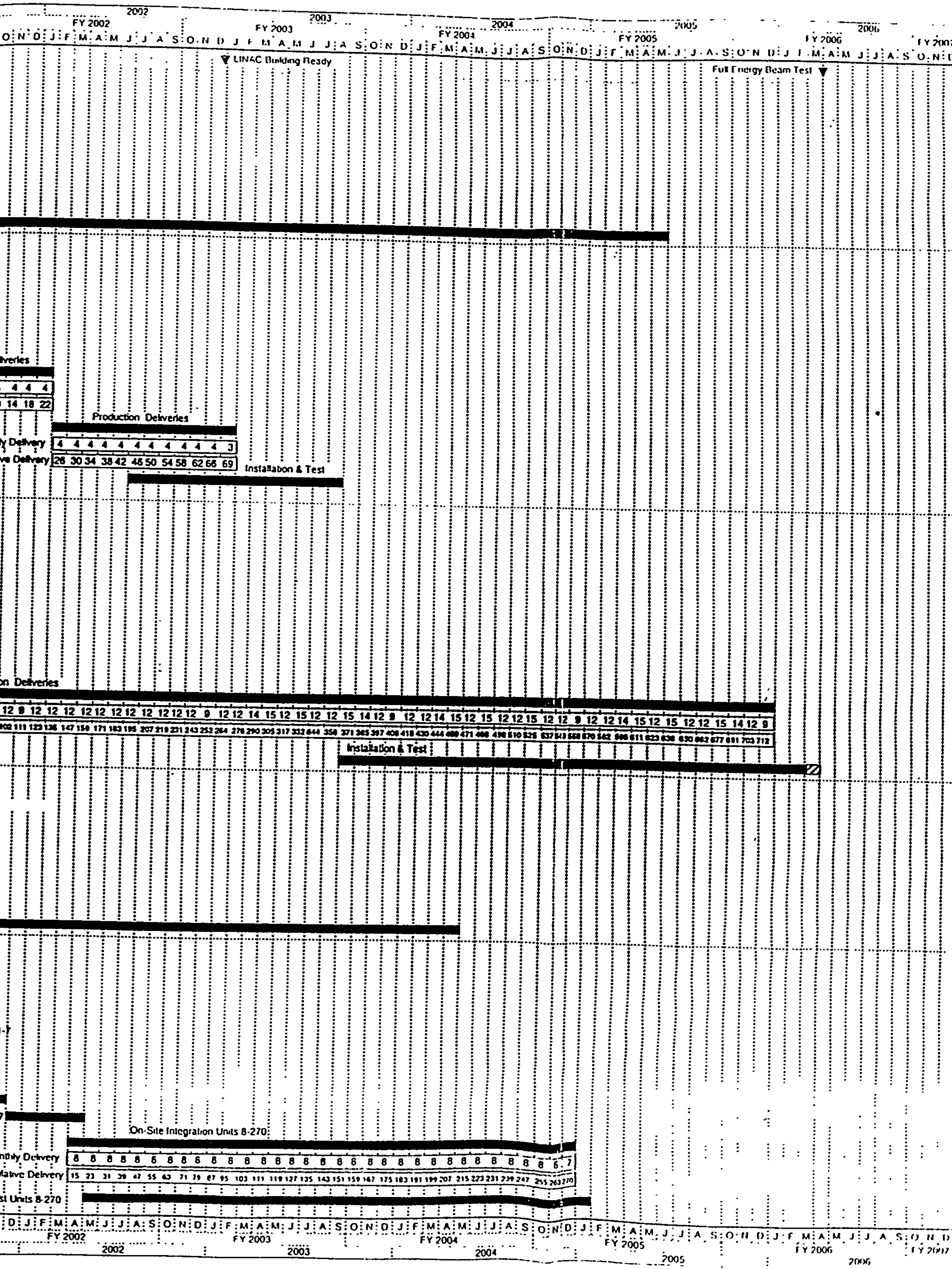
APT Room Temperature Manufacturin
Rate Production 6.7 thru 1300 MEV (



e Assessment

Flow for Baseline Configuration

CDTL - CCL - RF Power Supplies



Section 5.2.2 Preliminary Sch

APT Superconducting Manufactu
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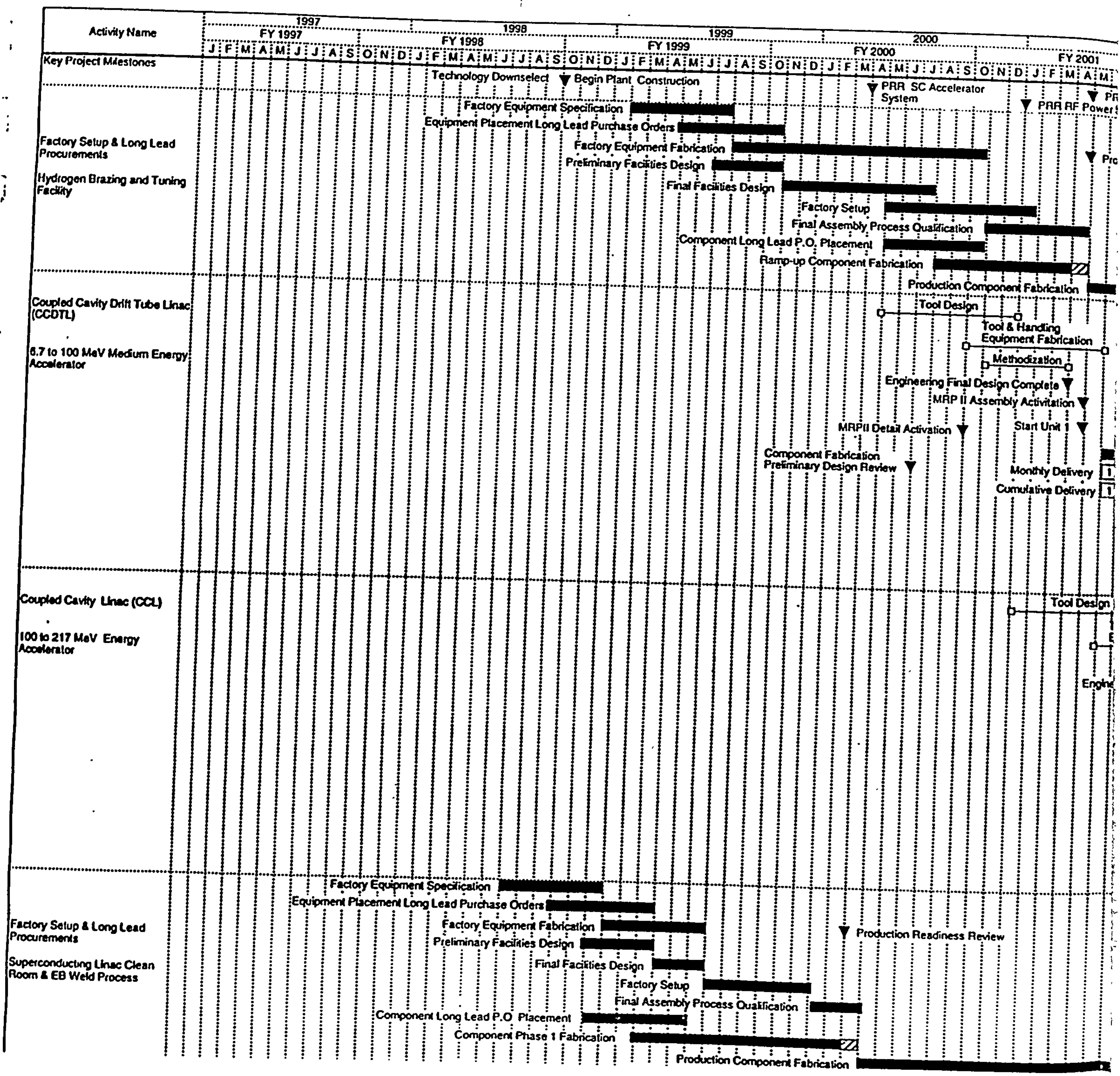
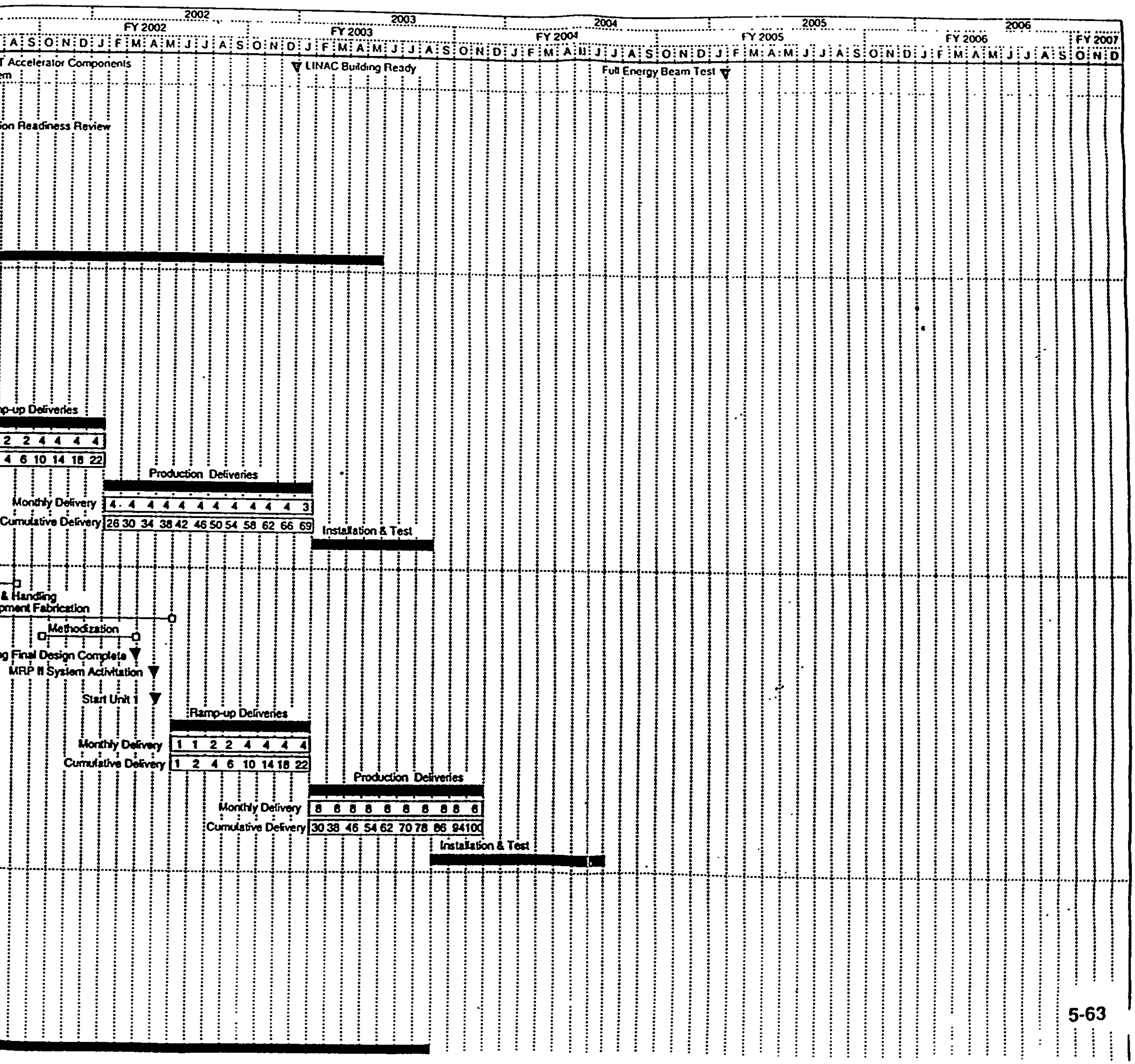


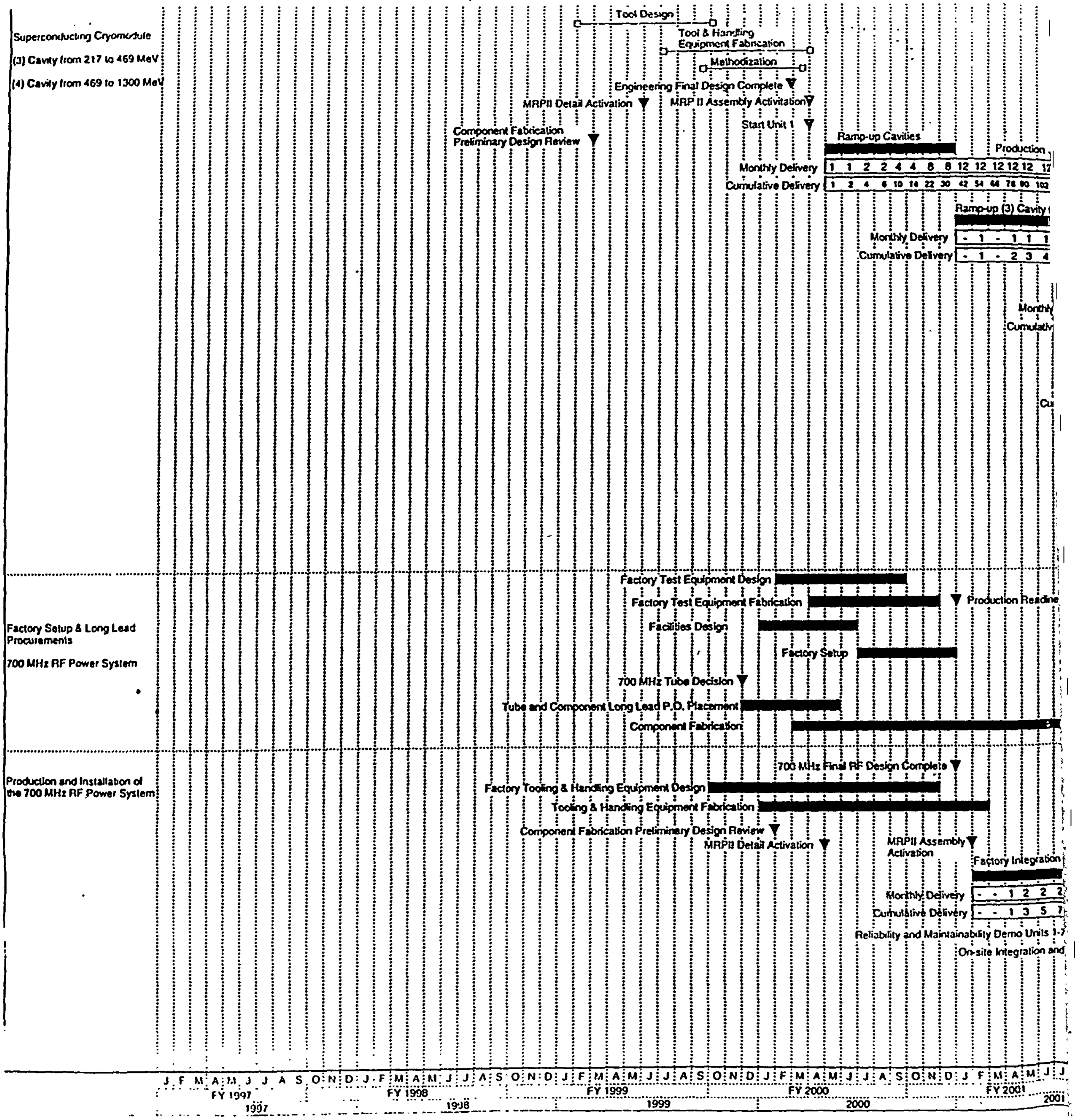
dule Assessment
ng Flow for Alternate Configuration
CDTL - CCL - SCL - RF Power Supplies



Section 5.2.2 Preliminar

APT Superconducting Manu

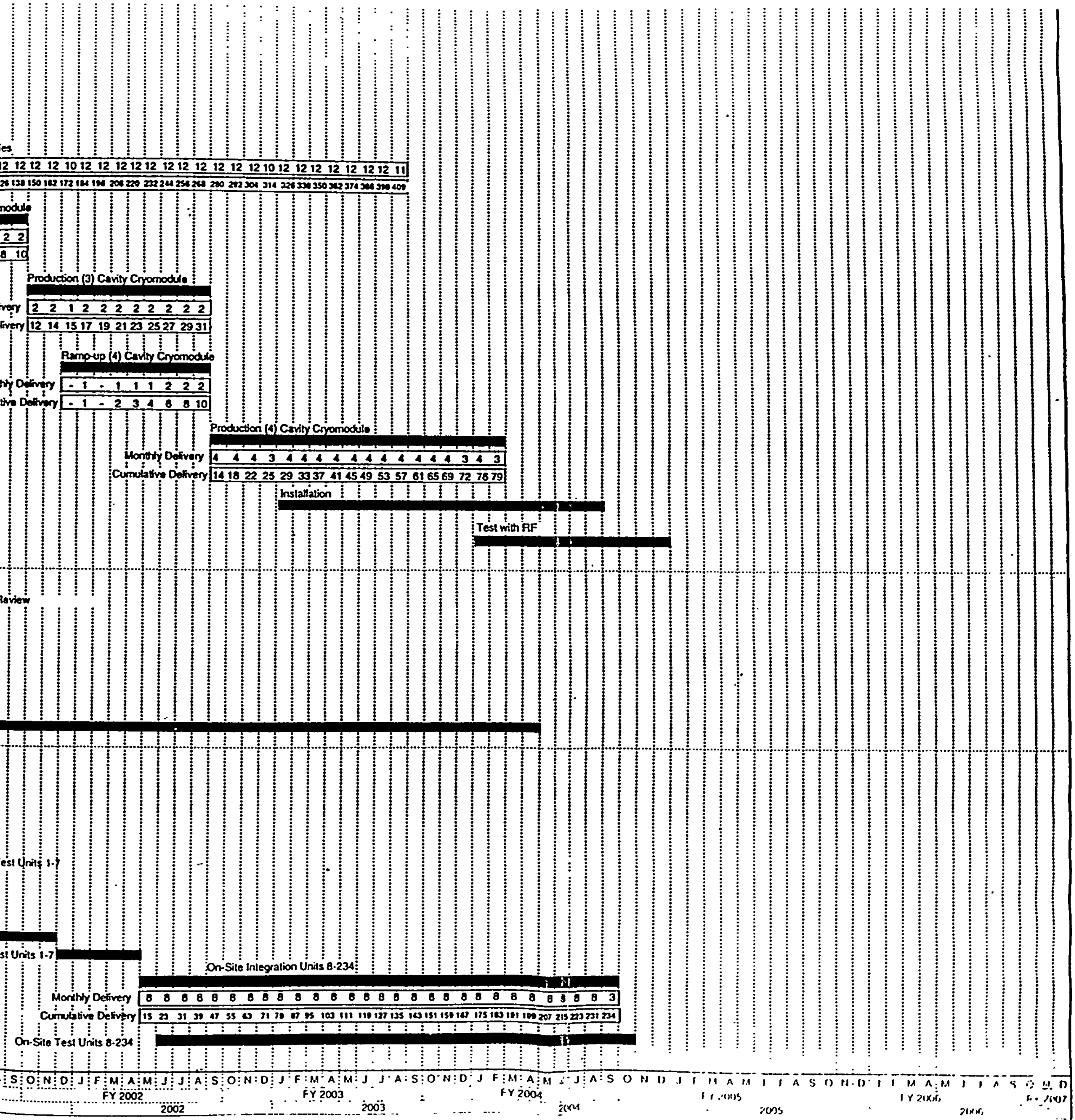
Rate Production 6.7 thru 1300 M



Schedule Assessment Continued

cturing Flow for Alternate Configuration

V CCDTL - CCL - SCL - RF Power Supplies



Appendix A

Comparison Of ASM & Early Los Alamos Capital Cost Estimates For Superconducting APT Linac

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Presentation at Los Alamos National Laboratory

25 September, 1996

High Dollar/High Percentage Differences

Cost Account	Δ to Los Alamos Estimate $k-95 Material	Labor	Comments
7-MeV RFQ	($268)	$5,474	• *ASM estimate based on prior Fabrication plan developed in 1993 for Los Alamos. ASM estimate also includes extra first physical segment.*
20-100 MeV CCDTL	($16,743)	$10,325	• *ASM projections based on in house manufacture of half cells*
100-1000 MeV SCL	($47,988)	$15,428	• *ASM projections based on in house manufacture of niobium cavities*
Instrumentation & Control	$4,588	$12,870	• *Higher level of professional software development effort included. Material figure depends on break with facility control equipment*
AC to DC Conversion and Distribution	($59,386)	($654)	• *Difference in contents probably exist. ASM estimates based on 12 pulse system.*
RF Transport	($19,941)	($1,704)	• *ASM line run lengths (and bends) probably not in concert with basis in Los Alamos figures*

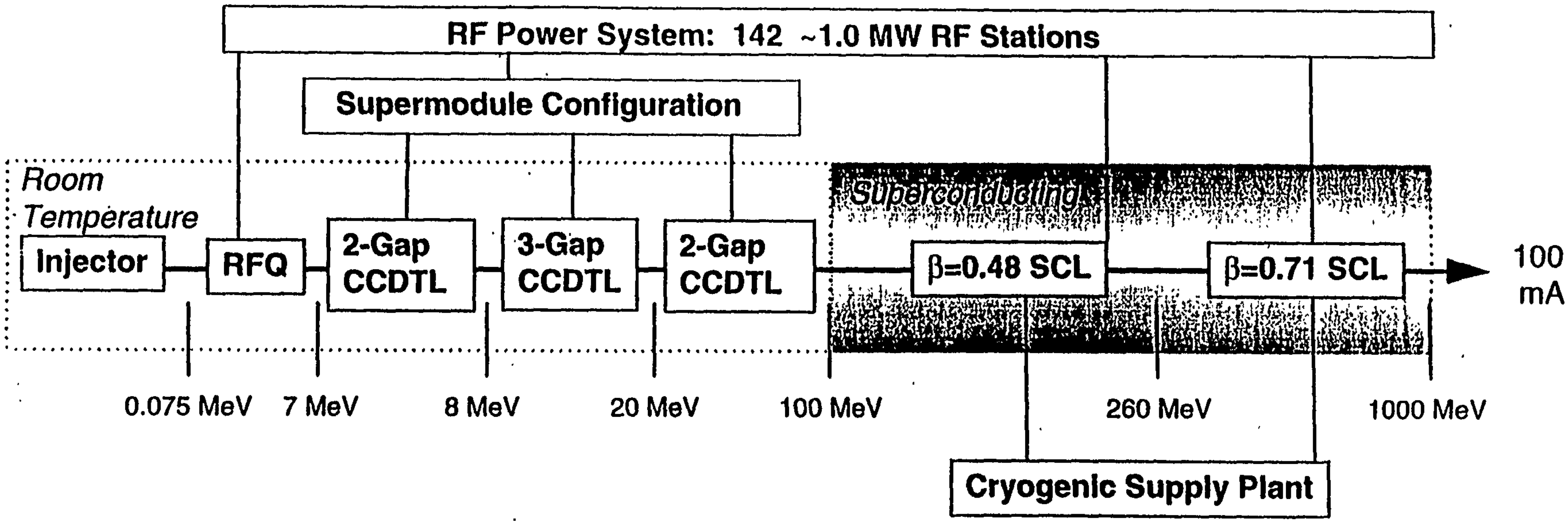
Highlights

- **Comparison with configuration details and cost estimate generated for "A Feasibility Study of the APT Superconducting Linac, 1995", LA-UR-95-4045, dated April 1996.**

- **ASM capital costs within 14% of Los Alamos estimate**
  - ASM predicts lower capital cost:
    - Accelerator: 3%
    - RF power: 28%
  - Los Alamos HEBT costs used:
    - ASM model modifications not ready in time

- **Individual differences exist at the component level**
  - Material:
    - Different "Make/Buy" assumptions and Government Furnished Equipment
  - Labor:
    - Different tasks (depends on above)
    - Different staffing approach to tasks
      - engineers instead of technicians (or reverse)
      - technicians instead of craft labor (or reverse)

September 95 Superconducting Accelerator



Details:

- **Room temperature configuration similar to configuration in draft Conceptual Design Report dated 7/19/96**
- **Superconducting configuration from, LA-UR-95-4045: "A Feasibility Study of the APT Superconducting Linac, 1995", dated April 1996**
  - cryomodules comprised of two four cell cavities, with external warm magnets.

Los Alamos Principle Accelerator Accounts

EEDB Account	Cost Categories	MATERIAL Costs	Other Costs	MAT & Other Costs	Labor Hours Prof	Labor Hours Tech	Labor Hours Craft	Labor Costs	Total Cost
271.1	Injector	$929	$0	$929	9,042	10,970	6,088	$1,970	$2,899
271.2	7-Mev RFQ	$4,000	$880	$4,880	6,100	6,200	2,400	$1,196	$6,076
271.4	20-MeV CCDTL	$4,100	$1,600	$5,700	11,800	9,200	5,500	$2,126	$7,826
271.7	100-MeV CCDTL	$12,000	$3,665	$15,665	34,900	22,200	13,000	$5,829	$21,494
271.8	Low-E Linac Intertank Assemblies	$12,021	$270	$12,291	4,218	6,132	2,360	$983	$13,274
271.1s	High Energy Superconducting Linac	$123,908	$16,000	$139,908	46,050	32,000	62,000	$9,016	$148,924
272.2s	High Energy Intertank Assemblies	$31,928	$1,020	$32,948	10,100	9,800	11,000	$2,121	$35,069
273.1	HEBT Transport Lines	$4,225	$613	$4,838	3,352	15,706	992	$1,571	$6,409
273.2	HEBT Beam Expanders	$3,203	$572	$3,775	3,674	10,052	528	$1,171	$4,946
274.1s	RF HV Generation and Distribution	$107,952	$0	$107,952	19,230	28,126	109,397	$6,960	$114,912
274.2s	RF Generators	$45,480	$0	$45,480	37,343	15,162	2,429	$5,306	$50,786
274.3s	Klystron Support Station	$11,315	$0	$11,315	8,559	22,236	17,856	$3,056	$14,371
274.4s	Low Level RF	$15,395	$0	$15,395	28,434	62,600	1,395	$7,858	$23,253
274.5s	RF transport	$60,361	$0	$60,361	21,368	71,760	12,526	$8,046	$68,407
274.6s	RF support Equipment	$11,238	$0	$11,238	18,552	37,762	2,919	$4,946	$16,184
274.7s	Klystron Primary Loop Cooling	$6,492	$0	$6,492	8,690	34,956	16,692	$3,995	$10,487
275.1s	SC Linac Vacuum Systems	$7,405	$683	$8,088	5,175	5,939	2,340	$1,073	$9,161
275.2s	SC Linac Primary Cooling Systems	$46,815	$1,243	$48,058	17,680	21,127	13,375	$3,864	$51,922
275.3s	SC Linac Support Stands	$2,891	$842	$3,733	7,815	8,979	8,200	$1,738	$5,471
276.1	Low Energy Linac Control Systems	$4,050	$0	$4,050	9,510	36,000	625	$3,762	$7,812
276.2s	High Energy Linac Control Systems	$8,863	$0	$8,863	28,730	86,950	1,250	$9,713	$18,576
276.3	HEBT Control Systems	$2,650	$0	$2,650	6,525	20,890	625	$2,300	$4,950
277.1s	Beam Diagnostics, Sensors	$5,520	$1,293	$6,813	4,359	26,748	-	$2,486	$9,299
277.2s	Beam Diagnostics, Electronics	$6,368	$2,224	$8,592	3,224	20,272	5,560	$2,014	$10,606
								TOTAL:	$663,110

Cost Accounts for Comparison

Account Name	Contains The Following Los Alamos Accounts
• Injector	[illegible]
• 7-MeV RFQ	
• 7 to 20 MeV CCDTL	[illegible]
• 20 to 100 MeV CCDTL	[illegible]
• 100 to 1000 MeV SCL	[illegible]
• Vacuum Systems	[illegible]
• Structural Support/Align System	[illegible] SC Linac Support Stands
• Thermal Control (Including Cryoplant)	[illegible] SC Linac [illegible] Cooling [illegible]
• Beam Diagnostics	[illegible] Beam Diagnostics, Sensors [illegible] Beam Diagnostics, Electronics
• Instrumentation and Control System	[illegible] Low Energy Linac Control Sy[illegible] [illegible].2s: High Energy Linac Control System
• AC to DC Conversion and Distribution	[illegible] RF HV Generation & Distribution [illegible].3s. Klystron Support Station
• RF Tubes, Peripherals, and Cooling	[illegible] RF [illegible] [illegible] [illegible] Klystron [illegible] Cooling [illegible]
• RF Transport	[illegible] RF Transport
• Support Structure	[illegible]

Top Level Costing Groundrules/Assumptions

- **LEDA program resolves major technology feasibility issues**
  - Prototype cavities produced for all accelerator structures
  - Contractor Preliminary & Final Design Engineering of components addressed in the LEDA are minimized
- **Estimate P&FD project management only**
  - Project management during fabrication or installation and check out periods is tracked in other non-accelerator cost accounts
- **ASM RFQ costs reflect electroforming, not brazing**
- **Same three labor rates used:**
  - professional: $110/hr
  - technician: $75/hr
  - craft labor: $25/hr
- **"Make/Buy" decisions reflect Northrop Grumman's manufacturing capabilities**
- **Government Furnished Equipment**
  - Raw material (Copper & Niobium)
  - 11th through nth units [first 10 units receive full burden]
    - RF station equipment
    - vacuum pumps (turbo and ion)
    - focusing magnets

Component Level Summary Cost Comparison ($k-95)

Cost Accounts	Los Alamos	ASM	Delta - $k	%
Injector	$2,899	$2,513	($386)	-13%
7-MeV RFQ	$6,076	$11,282		
7 to 20-MeV CCDTL	$10,395	$9,251	($1,144)	-11%
20 to100-MeV CCDTL	$32,199	$25,782		
100-1000 MeV SCL	$183,993	$151,433		
Vacuum Systems	$9,161	$9,237	$76	1%
Structural Support & Alignment	$5,471	$8,822	$3,351	61%
Thermal Control	$51,922	$55,369	$3,447	7%
Beam Diagnostics	$19,905	$19,827	($78)	0%
Instrumentation & Control	$26,388	$43,855		
HEBT	$16,306	$16,306	$0	0%
AC to DC Conversion and Distribution	$129,282	$69,243	[illegible]	[illegible]
RF Tubes, Peripherals, & Cooling	$84,525	$91,221	$6,696	8%
RF Transport	$68,407	$46,762	[illegible]	[illegible]
Support Structure and Cabling	$16,184	$8,710	($7,474)	-46%
Major Assembly Cost Comparison				
Accel	$296,485	$282,002	($14,483)	-5%
HEBT	$16,306	$16,306	$0	0%
Cryo	$51,922	$55,369	$3,447	7%
SUBTOTAL less HEBT:	$348,407	$337,370	($11,036)	-3%
RF	$298,398	$215,935	($82,462)	-28%
Total	**$663,110**	**$569,612**	($93,499)	-14%

High Dollar/High Percentage Differences

Cost Account	Δ to Los Alamos Estimate $k-95		Comments
	Material	Labor	
7-MeV RFQ	($268)	$5,474	• *ASM estimate based on prior Fabrication plan developed in 1993 for Los Alamos. ASM estimate also includes extra first physical segment.*
20-100 MeV CCDTL	($16,743)	$10,325	• *ASM projections based on in house manufacture of half cells*
100-1000 MeV SCL	($47,988)	$15,428	• *ASM projections based on in house manufacture of niobium cavities*
Instrumentation & Control	$4,588	$12,870	• *Higher level of professional software development effort included. Material figure depends on break with facility control equipment*
AC to DC Conversion and Distribution	($59,386)	($654)	• *Difference in contents probably exist. ASM estimates based on 12 pulse system.*
RF Transport	($19,941)	($1,704)	• *ASM line run lengths (and bends) probably not in concert with basis in Los Alamos figures*

RF System Highlights

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18 December 1996

Mapping Between LANL Elements and ASM Elements

LANL RF Subdivisions		ASM Code RF Subdivision
High Voltage Power Supply	====>>	AC-DC Conversion -- Remove matching transformer -- Includes mod anode modulator
Klystron	===================>>	RF Tube & Peripherals -- Includes lead garage, window cooling, sensors, etc.
RF Transmission	============>>	RF Transport -- W/G, arc detectors, filter, circulator, loads, splitter, couplers, W/G switches, sensors, etc.
Transmitter Electronics -- Includes mod anode modulator	========>>	Low Voltage Power Supplies RF Source & Driver Global Monitoring & Control RF Cooling (less pumps and distribution) -- Includes valves, manifold, sensors, gauges, etc. Structure, Interconnecting Cables, etc.
RF Control	================>>	Phase & Amplitude Control

Data Inputs for Updates to Trades -- RF Tubes

- **Klystron**

  Efficiency - 65% maximum at saturation

  Range of 25,000 to 35,000 -- used 25,000 hours

  Total margin (design, operating, derating) -- 10%

  Cost -- $215 K for 4 lot of 350 MHz klystron

  Cost -- $235 K for 1 lot 700 MHz klystron

- **HOMIOT**

  Efficiency - 73% maximum at saturation

  Range of 25,000 to 35,000 -- used 25,000 hours

  Total margin (design, operating, derating) -- 10%

  Cost -- $175 K for 1 lot of 700 MHz HOMIOT

Data Inputs for Updates to Trades -- Circulator

- **350 MHz Circulator**

  Loss 0.05 dB

  Cooling required -- 25 C inlet water

  Cost -- $150 K for assumed 3 lot circulator

  Cost -- $17.2 K for the circulator load in 1 lot

- **700 MHz Circulator**

  Loss 0.07 dB

  Cooling required -- 25 C inlet water

  Cost -- $140 K for assumed 6 lot circulator

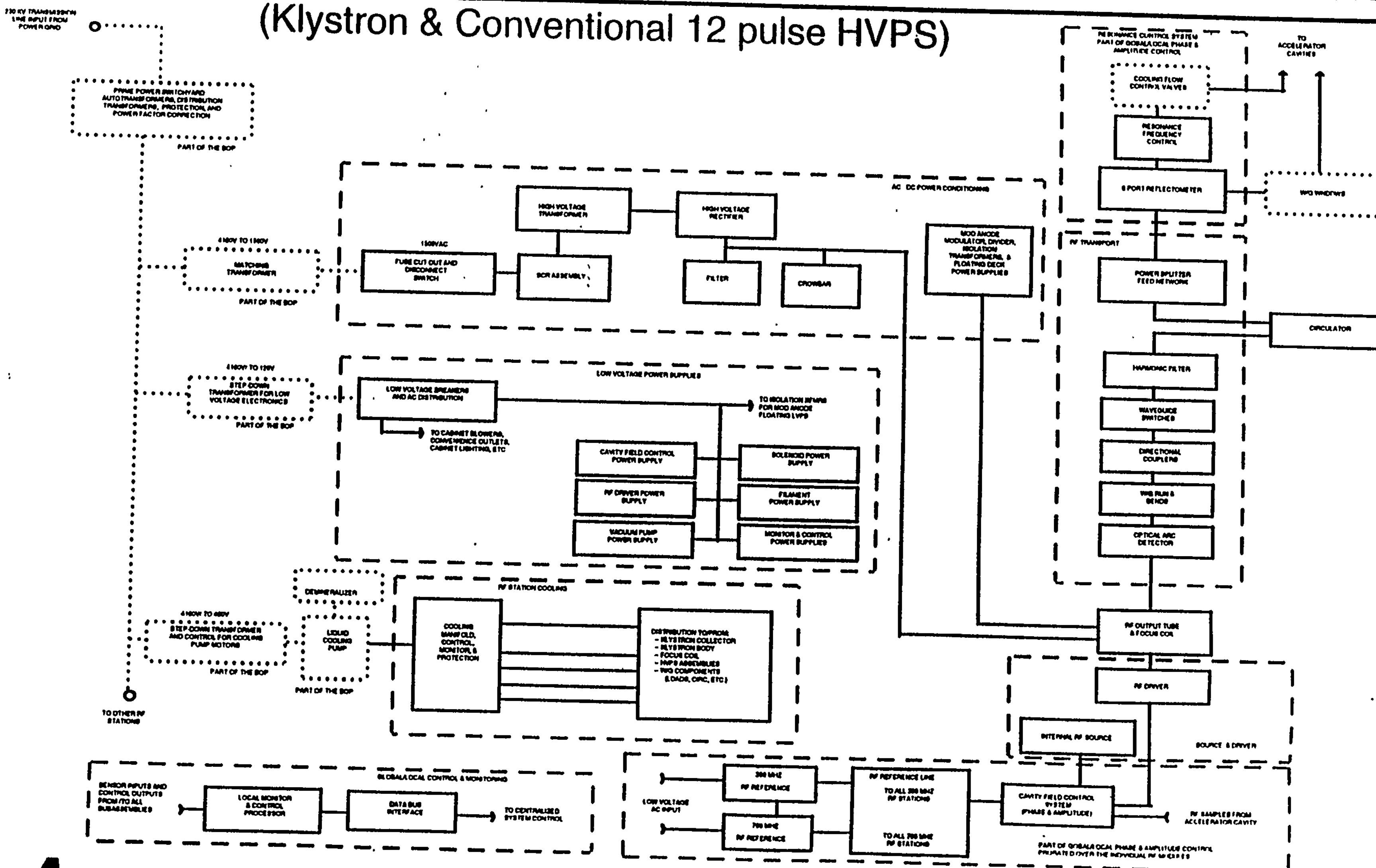
  Cost -- $16.7 K for the circulator load in 1 lot

- **Total losses in RF transport**

  5% including circulators

RF STATION BASELINE FOR THE NORMAL CONDUCTING ACCELERATOR

(Klystron & Conventional 12 pulse HVPS)

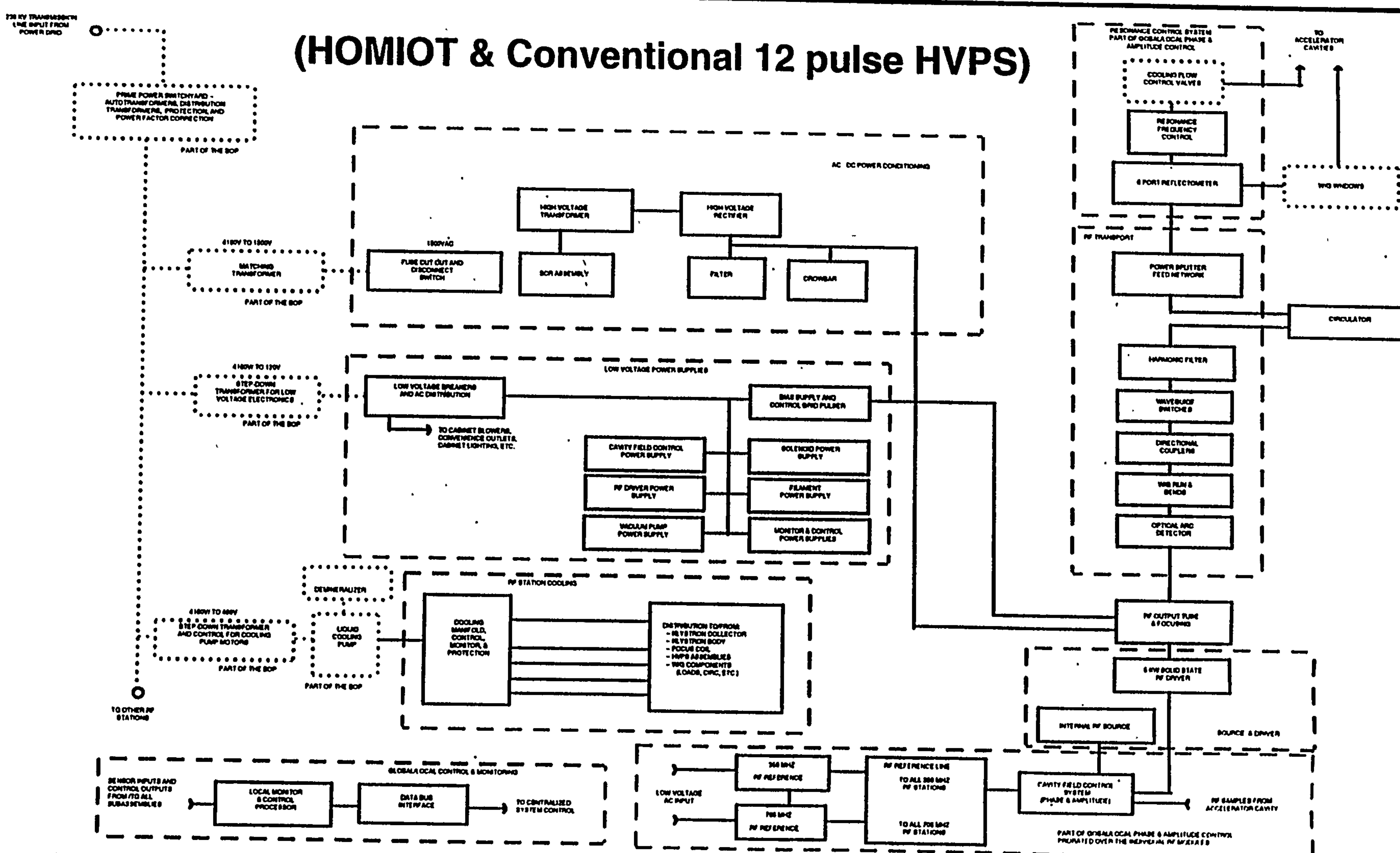


Accelerator Production of Tritium

RF STATION TRADE FOR RF OUTPUT TUBE

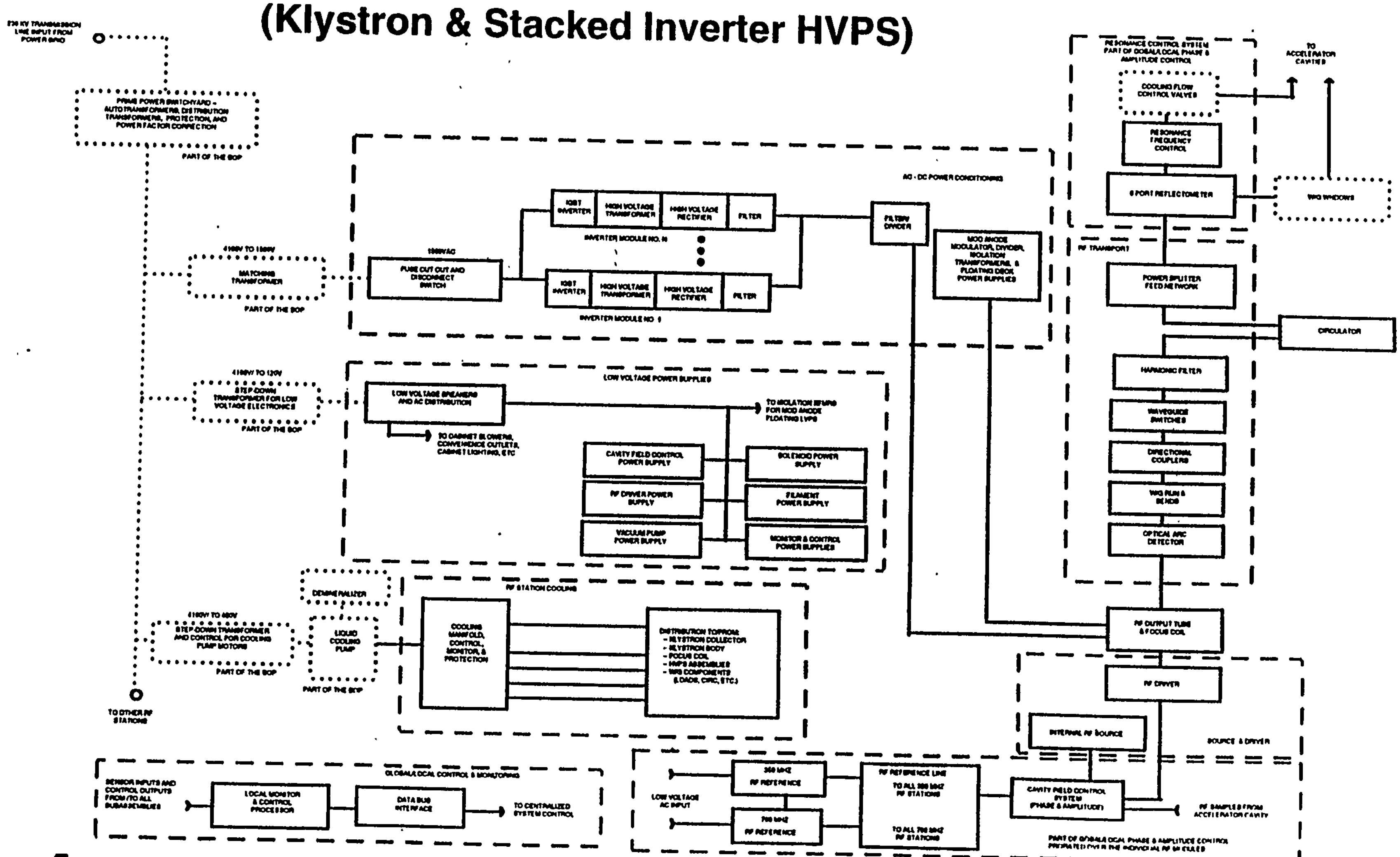
2 DEC 1996

(HOMIOT & Conventional 12 pulse HVPS)



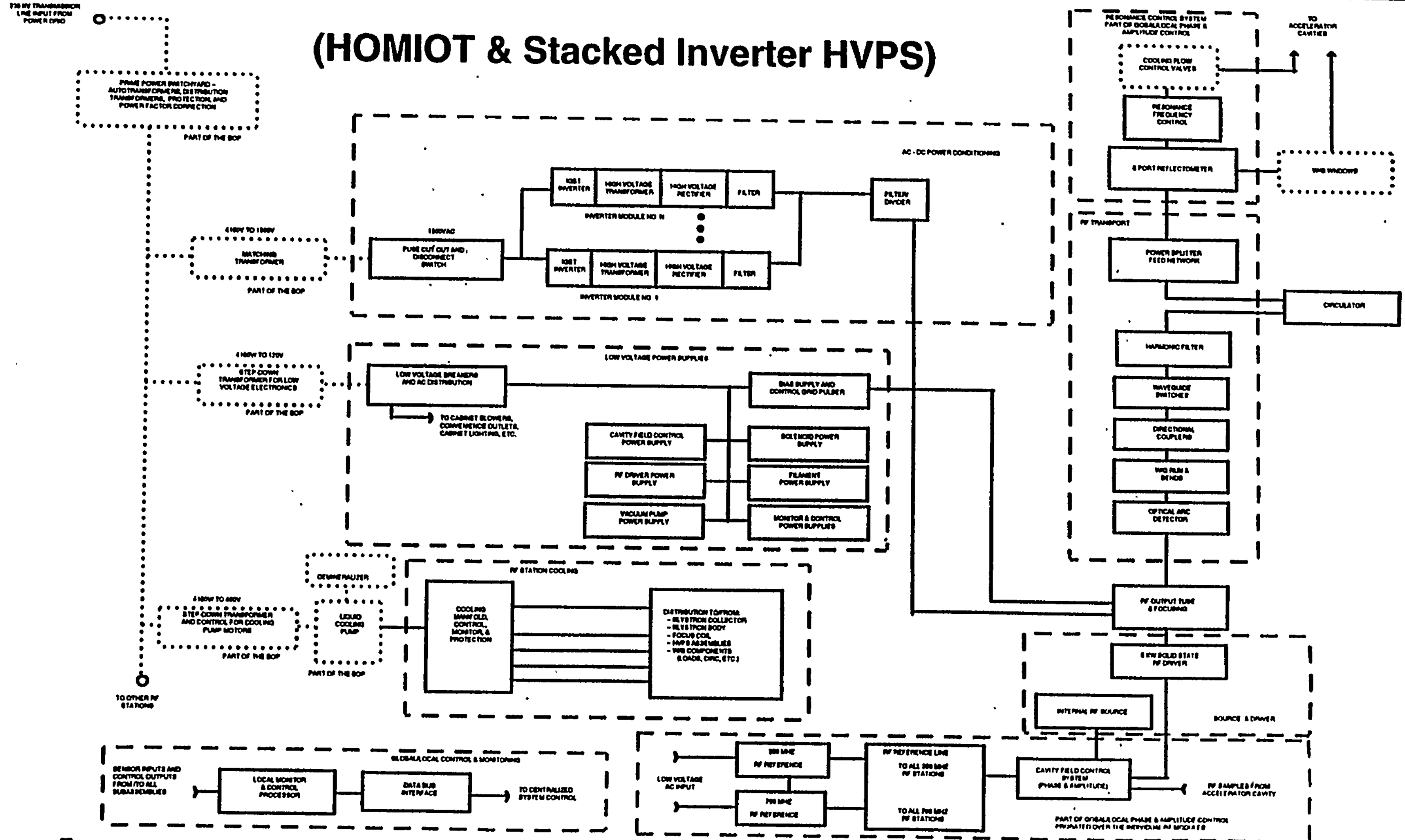
RF STATION TRADE FOR HV POWER SUPPLY

(Klystron & Stacked Inverter HVPS)



RF STATION TRADE FOR RF OUTPUT TUBE

(HOMIOT & Stacked Inverter HVPS)



Results Summary for RF Station Trades

Case	Baseline	Alt #1	Alt #2	Alt #3	Alt #4
Accelerator Type	NC	SC	SC	SC	SC
Tube Type (700 MHz)	Klystron	Klystron	HOMIOT	Klystron	HOMIOT
Number of Tubes	273	237	237	237	237
Power Supply Type	12 Pulse	12 Pulse	12 Pulse	Modular	Modular
RF Power (MW)					
-- into cavities for 2 kg/yr	191	142	142	142	142
-- into cavities for 3 kg/yr		191	191	191	191
-- output capability from tubes	274	238	238	238	238
AC Power Input (MW)					
-- for 2 kg/yr	421	339	287	353	300
-- for 3 kg/yr		400	339	417	354
Total RF Equipment Cost ($)	389.3	342.9	335.0	364.8	354.7
Average Cost per Station (K$)	1426	1447	1414	1539	1497
Dollars per RF Watt into Cavities					
for 2 kg/yr	2.04	2.41	2.35	2.56	2.49
for 3 kg/yr		1.79	1.75	1.91	1.86

Assumptions for Scheduling of Production RF Stations

- Start preliminary design activity on 700 MHz klystron & HOMIOT RF Station configurations and downselect after tube selection is made or expedite the tube effort to make the downselect earlier
- Large percentage of the components can be bid competitively
- Costs reflect learning curves for high volume production
- Integrate RF Stations at directly at site after all 350 MHz and first seven 700 MHz RF stations are done at contractors facility
- Preliminary design phase assumes that the design has progressed to the point where manufacturing drawings exist and planning for the construction phase can start
- Manufacture small quantity of key assemblies during the end of the preliminary design phase to verify manufacturability prior to start of full production
- Final design will update the manufacturing drawings to ensure producibility
- Start installation prior to final completion of klystron gallery (10/1/2001) to relieve schedule concerns and minimize the need for large storage space for production equipment

RF Station Production Manufacturing Schedule -- (Sheet 1 of 3)

see Microsoft project file -- SCHED4.mpp

RF Station Production Manufacturing Schedule -- (Sheet 2 of 3)

see Microsoft project file -- SCHED4.mpp

RF Station Production Manufacturing Schedule -- (Sheet 3 of 3)

see Microsoft project file -- SCHED4.mpp

Appendix C

PARAMETRIC STUDY OF EMERGING HIGH POWER ACCELERATOR APPLICATIONS USING ACCELERATOR SYSTEMS MODEL (ASM)

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Abstract

Emerging applications for high power rf linacs include fusion materials testing, generation of intense spallation neutrons for neutron physics and materials studies, production of nuclear materials and destruction of nuclear waste. Each requires the selection of an optimal configuration and operating parameters for its accelerator, rf power system and other supporting subsystems. Because of the high cost associated with these facilities, economic considerations become paramount, dictating a full evaluation of the electrical and rf performance, system reliability/ availability, and capital, operating, and life cycle costs.

The Accelerator Systems Model (ASM), expanded and modified by Northrop Grumman during 1993-96, provides a unique capability for detailed layout and evaluation of a wide variety of normal and superconducting accelerator and rf power configurations. This paper will discuss the current capabilities of ASM, including the available models and data base, and types of trade studies that can be performed for the above applications.

Introduction And Background

High power rf-driven ion linacs are currently being considered for a variety of applications including, but not limited to:

- Spallation neutron production for scientific and materials studies (e.g., European Spallation Source [ESS], US National Spallation Neutron Source [NSNS])
- ~14 MeV neutron production for fusion materials testing (e.g., International Fusion Materials Irradiation Facility [IFMIF])
- Production of nuclear materials (e.g., Accelerator Production Of Tritium [APT])
- Destruction of high-level nuclear waste (e.g., Accelerator Transmutation of Waste [ATW])

The Accelerator Systems Model (ASM), expanded and modified by Northrop Grumman since 1993, provides a unique capability for detailed layout and evaluation of the wide variety of rf linac and rf power configurations. This capability, recently used to support the IFMIF accelerator design effort (as well as internally funded efforts involving higher energy linacs), provides the following features:

- Ability to model ion linac configurations based upon a large number of existing and recently proposed normal and superconducting linac structures, operating over a wide range of rf frequencies
- Detailed tracking of the linac's cell-by-cell configuration and the electrical and rf power system performance
- Generation of detailed component inventory that includes all accelerator systems and dedicated facilities
- System reliability, availability, maintainability (RAM) modeling for estimation of operational availability and the cost of component replacement and/or refurbishment
- Cost analysis capability which encompasses capital, construction, and annual operating costs, resulting in a single net present value life cycle cost estimate.

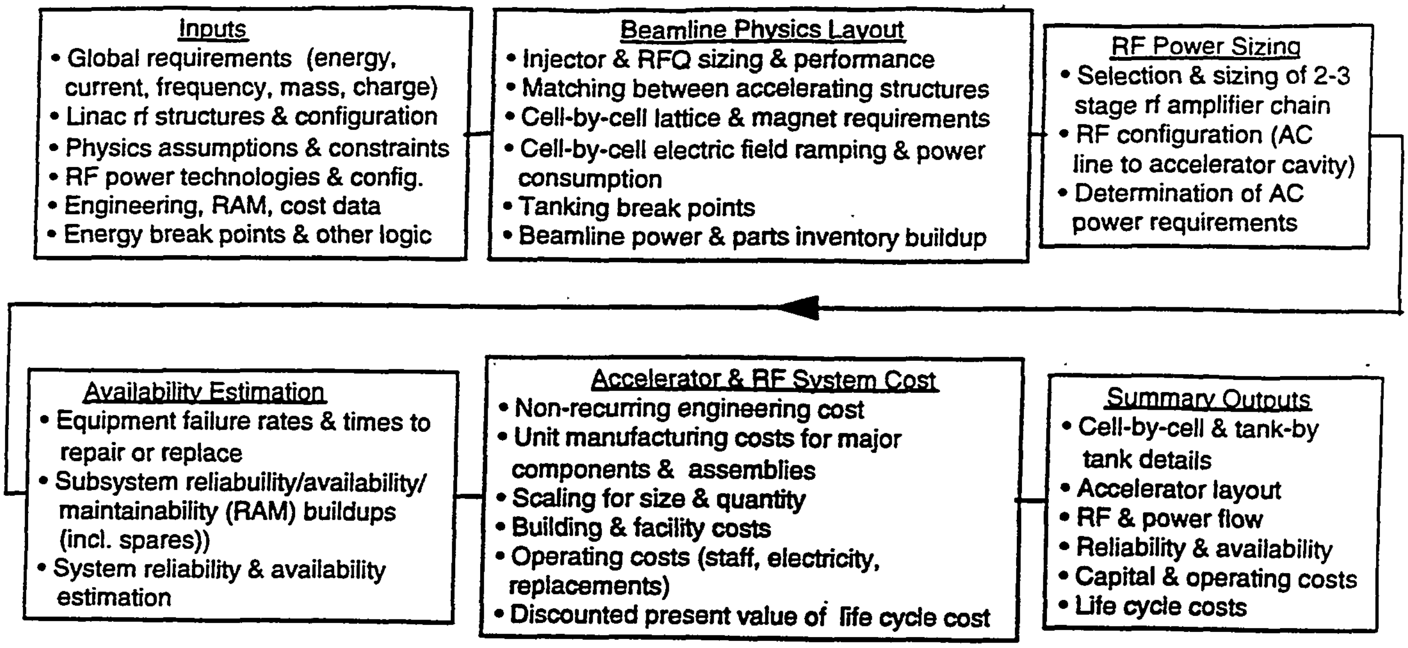
ASM allows the user to consider many linac configurations and technology trades, in a limited time, using a complete set of data and a consistent set of modeling algorithms.

The on-going physics and engineering modeling effort of ASM is now concentrating on improvement of existing models (e.g., diagnostics, instrumentation and control and cryogenics), implementation of an automated capability for parameter trades, and adaptation of the code for pulsed ion linacs. Future ASM variants dedicated to applications involving electron beam accelerators, free electron lasers, ion cyclotrons and ion storage rings are envisaged.

ASM Calculational Flow

The ASM code is driven by a Macintosh™ Graphic User Interface (GUI) that provides a user interactive, on-screen format for data input. In addition, the code reads several formatted files that convey engineering, cost and RAM data.

Figure 1. Accelerator Systems Model (ASM) Calculational Flow



As shown in Fig. 1, the first series of Fortran routines use the input data to establish a cell-by-cell layout of the accelerator, starting at the ion injector and proceeding through all of the major rf structures, completing each at a specified energy breakpoint. A generalized set of algorithms is used to match the synchronous phase and the longitudinal and transverse phase advances from structure to structure.

The electric field is linearly ramped within an rf tank according to any of several criteria (e.g., proportional to particle velocity, β, up to a limiting value). Tank sizing may be specified according to the available rf power, energy break points or other user inputs. When the layout is completed, the rf power requirements and an inventory of linac components (see Fig. 2) is passed to the subsequent routines.

Fig. 2 DTL Parts Identification Schematic Illustrating Level Of Cost Estimation Incorporated Into ASM Model

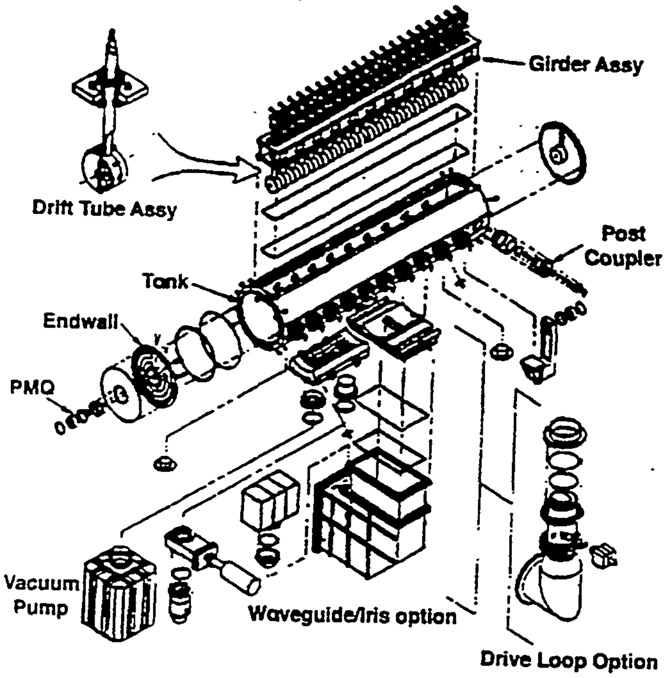
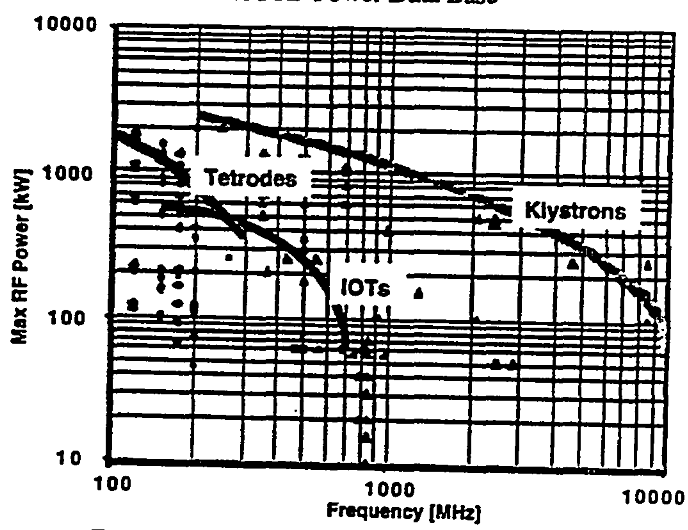


Fig. 3 CW-Rated RF Output Amplifiers Currently Included In ASM RF Power Data Base



The next set of ASM routines are used to size and configure the rf power system, which is critical to the overall evaluation because it represents the largest cost component of the accelerator, dominates the electric power requirement and plays a major role in the system availability. As a first step, ASM reviews the required sizes and frequencies of rf sources and compares them with its rf amplifier data base, illustrated in Figure 3. The code selects the tube with the best operational efficiency, then lays out the remainder of the rf system including the driver tube(s), peripheral equipment, high voltage equipment and rf transport components. Based upon the inventory of rf components and their various rf and electrical efficiencies, the electrical power requirement of the rf system is estimated.

A third set of ASM routines is used to estimate the overall operational availability of the accelerator (during scheduled operation). Starting with a RAM library containing the failure rates (mean time before failure, or MTBF) and repair times (mean time to repair, or MTTR) of the constituent equipment, the ASM RAM routines process the configuration and parts inventory data to develop estimates of the RAM performance of individual subsystems. These are combined (with consideration of spares and redundancies) to develop an overall estimate of the system reliability and availability. The results are also used to predict the rates of replacement of major components.

The next set of ASM routines provide estimates of the capital, operating, and life cycle costs for the major subsystems of the accelerator. Using the parts inventory, these routines develop engineering, fabrication labor and materials cost estimates. The engineering estimates are comprised of both non-recurring design and development activities for the first unit and recurring engineering for subsequent units. Where large quantities of parts or components are required, learning curve techniques are used to model the decreasing cost of unit production or acquisition.

Annual operating cost estimates are developed from the electric usage, component refurbishment/replacement requirements and facility staffing estimates. A life cycle cost estimate that combines the capital costs, with projections of the facility construction costs and the annual operating costs is also developed. Standard net present value analysis is used to represent the life cycle cost as a single value.

Trades That Can Be Performed Using ASM

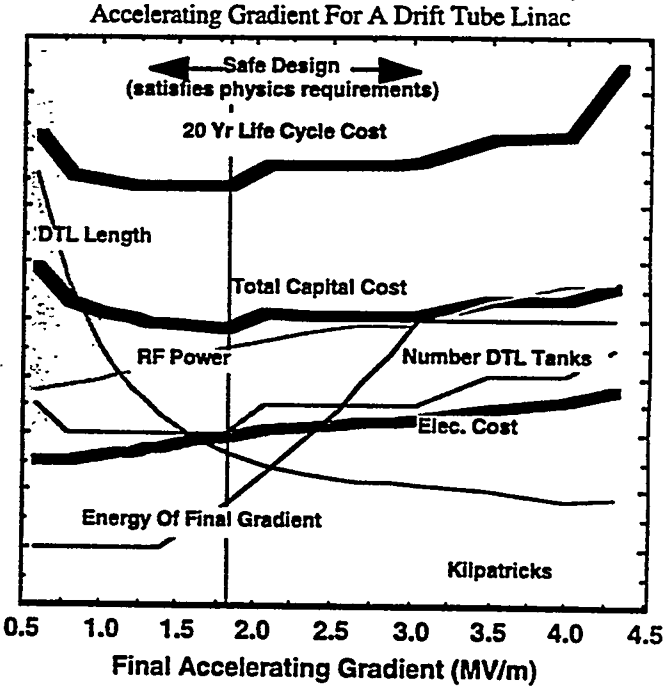
The types and applicabilities of trades currently supported by ASM are indicated in Table 1. In the table, a "√" indicates that the code has already been used to perform the indicated type of trade, a "•" indicates that the trade should be considered for the indicated application, and "N/A" indicates that the trade is not applicable.

An example of a recent trade involves the selection of the preferred accelerating gradient for a drift tube linac (DTL). As shown in Figure 4, the capital and operating costs increase at high gradient due to the increased rf power consumed in the structure, which leads to larger rf power requirements and larger electricity requirements. As the gradient is decreased the rf power requirement also decreases, but the DTL length and the number of rf tanks increase, decreasing the rf power per tank and ultimately increasing the overall life cycle cost. The best balance between these trends results at a gradient of 1.8 MV/m, where the life cycle cost is minimized.

Table 1. Current ASM Trade Study Capabilities

	Linac Application		
Candidate Trade Study	IFMIF	ATW	NSNS
Beam Pulse Length	N/A	N/A	•
Alternative Accelerating Structures	√	•	•
Normal vs. Superconducting	√	•	•
Transition Energies & Matching	√	•	•
Beam Energy vs. Current	N/A	√	•
Accelerating Gradient	√	√	•
RF Frequency	√	•	•
Frequency Doubling	√	•	•
Current Funneling	N/A	•	N/A
Multiple vs. Single Beamlines	√	√	N/A
Multiple vs. Single Ion Injectors	√	•	N/A
Design Optimization vs. Plant Life	√	•	N/A
RF Amplifier Technology	√	√	•
RF Tanking	√	√	•
RF Pre-Amplifier Staging	√	•	•
RF Amplifier Redundancies	√	•	•
High Voltage Power Technology	N/A	•	•
RAM Trades	√	√	•

Fig. 4 Example Of Use Of ASM To Determine Optimal Accelerating Gradient For A Drift Tube Linac



Acknowledgments

The Northrop Grumman Version of ASM is a product of G. H. Gillespie Associates, Inc. Figure 2 was provided courtesy of Los Alamos National Laboratory