

SYSTEM MODEL FOR LIFE CYCLE COSTING

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The policy on Life Cycle Costing within the Navy is set forth in SECNAVINST 4000.31 of 7 December 1970 (1). This policy requires that the techniques discussed in DOD Guide on Life Cycle Costing Procurements (2) be applied to as many procurements as feasible. This policy is further implemented by NAVMAT Note 4000 of 10 March 1971 (3) which applies the technique to less than complete weapon system acquisition. In paragraph 2 of this Note it is stated, "Life Cycle Costing is a technique of minimizing life cycle costs by considering the cost of as many logistics elements as possible during the acquisition process." The policy addressed by these instructions primarily deals with the trade-off that can be made to minimize the cost of a system to the Navy during the acquisition process. The policy, because of the recognized difficulty in its implementation, is limited to less than complete systems.

The acquisition process for weapon systems and related or supporting systems is complex and lengthy. It would be desirable to include consideration for the total cost of ownership as a decision factor in the concept formulation phase of system development. In order to do this it is essential that the effect of various decisions be understood when Life Cycle Costing influencing factors, such as reliability, maintainability, parts support, test equipment, documentation, and other related factors, are being established. This paper sets forth a systems approach to the development of a Cost of Ownership Model (COM) that would provide the quantitative basis for the trade-off decisions that must be made early in the development process.

COM Objectives. The basic objectives of the design versus logistics trade-off study is to minimize the total cost of ownership by investigating various alternatives under dynamic conditions.

In order to provide a meaningful insight into the cost of ownership of a system, the model must be representative of the real world. A good analytic approximation of the system can be obtained by considering the design/logistics policy determination as a dynamic information-feedback system. The

system dynamics technique set forth in Industrial Dynamics by J. W. Forrester (4) basically fits these criteria.

The system dynamics approach has the advantage over the method set forth in LCC-3, Life Cycle Costing Guide for Systems Acquisition (Interim), June 1973 (5), by introducing change in the cost of ownership as a function of time by redesign of the system or by revisions to the logistics policy. The system dynamics approach also takes the interaction between various sectors of the system into account.

The same system dynamics approach for military training systems was set forth in "The Application of System Dynamics Techniques to the Modeling of the Military Training System," by Amico, Burtle and Gardner (6). In that case, the technique was applied to the problem of the optimum start time for the development of a training device with relation to the operational system schedule.

To be effective, the design-logistics trade-off analysis must be introduced in the concept phase of a project well before contract award. In the case of a training device, this would begin during the time that the Military Characteristics are being drafted. In this way, the requirement for trade-offs can be reflected in that document. The Design Approach (an in-house technical document) would contain the results of such an analysis, the optimum design/logistics approach for that device. Basic system design/support decisions which minimize the life cycle cost would then be established by the Government in its specifications and support requirements prior to initiating procurement.

Although this task is difficult, it is by no means impossible. Major factors which affect life cycle cost and the design/logistics policies which affect them have been well identified. What is not generally understood is the effect of various design/logistic policies in the cost of ownership. Through parameter search techniques the sensitivity of basic design/logistic policies can be tested. Major factors which influence cost of ownership can be addressed so that maximum benefit can be achieved.

Cost of Ownership Model. In developing the model for total cost of ownership, one must consider the complete development cycle of a training device. The actual system which is being modeled is nonlinear, principally because of the human element involved. The system is also time varying because of change in policy which occurs as a function of time. Even with such a complex system it is possible to obtain useful data about its behavior through the simulation of costs of a simple linear, time-varying model.

The basic question addressed by the Cost of Ownership Model can be stated as follows, "What design/logistics policies minimize the cost of ownership based on a given set of constraints?"

An overall training system flow diagram is presented in Figure 1 of reference 6. Although it would be possible to expand that basic model for the purpose of this investigation, the COM developed in this investigation is treated as an independent subsystem of the training system model. The flow diagram for this COM is shown in Figure 1.

The major factors which influence the cost of ownership fall into two categories, (1) Design and (2) Logistics/Support. The two factors are directly related. There are also a number of constraints which influence cost of ownership. The major constraints are:

1. Performance
2. Staffing Levels (Max-Min)
3. Usage
4. System Policies (Supply, Repair, Transportation).

Before describing the flow diagram shown in Figure 1, a brief description of system dynamic modeling techniques is provided. A complete description of the modeling techniques and the programming instruction are contained in reference (4). The basic elements of the model are levels, rate, and auxiliaries.

A level represents the amount of a quantity, such as percent design remaining, spares inventory, or total cost of ownership. Rate (values) controls the flow into and out of the level blocks. The failure rate determines the rate at which inventory is depleted. The mean time to repair determines the rate at which items being repaired are returned to the inventory. Auxiliaries are used to establish the interaction between level and rates and includes the delay which occurs in the system. The redesign rate of a system to improve its maintainability or reliability is determined by the failure rates, repair rates, and spare inventory levels.

Cost of Ownership Flow Diagram. The cost of ownership flow diagram shown in Figure 1 is a simplified diagram which shows the basic interaction between major sectors of the system. For the purpose of this analysis, a number of simplifying assumptions were made. These assumptions will be identified in this discussion and in the detailed discussion of the model.

The major sectors of the system are the assembly sector, the repair parts sector, and the maintenance personnel sector. The last sector required to complete the model is the cost sector. A number of factors which influence cost of ownership, such as test equipment (built in or off-line) and maintenance documentation, have not been included. Since the purpose of this model is to demonstrate the applicability of system dynamics for optimizing design/support Policies, their omission is not considered critical.

The assembly sector performs two basic functions in the model. First, it enables the cost of design and manufacturing to be accumulated as a function of various reliability-maintainability policies. It also establishes the feedback loop for the redesign of assemblies if the failure rate is excessive.

Once a system is in the inventory, the costs associated with developing and producing the equipment are replaced by the costs of operating and maintaining a system for its useful life. Although the cost per time increment is small, their accumulation over many years frequently exceeds the acquisition cost of a system. The costs associated with the operational phase are accumulated in the remainder of the flow diagram.

The inventory and repair-backlog levels are used to generate the utility cost and the loss of training time costs. These levels also establish the failure and repair rates of assemblies. For the purpose of the analysis, the assumption is made that when an assembly fails in the system, the time to repair the system (replace the defective assembly) is in the order of minutes. Since the model will use an integrating interval of one week, the time to place the system in operation will not be significant. However, when a certain number of assemblies are in the repair backlog, the trainer will be assumed down and the costs associated with lost training time will be accumulated. The high repair backlog also initiates the redesign of assemblies to improve their reliability.

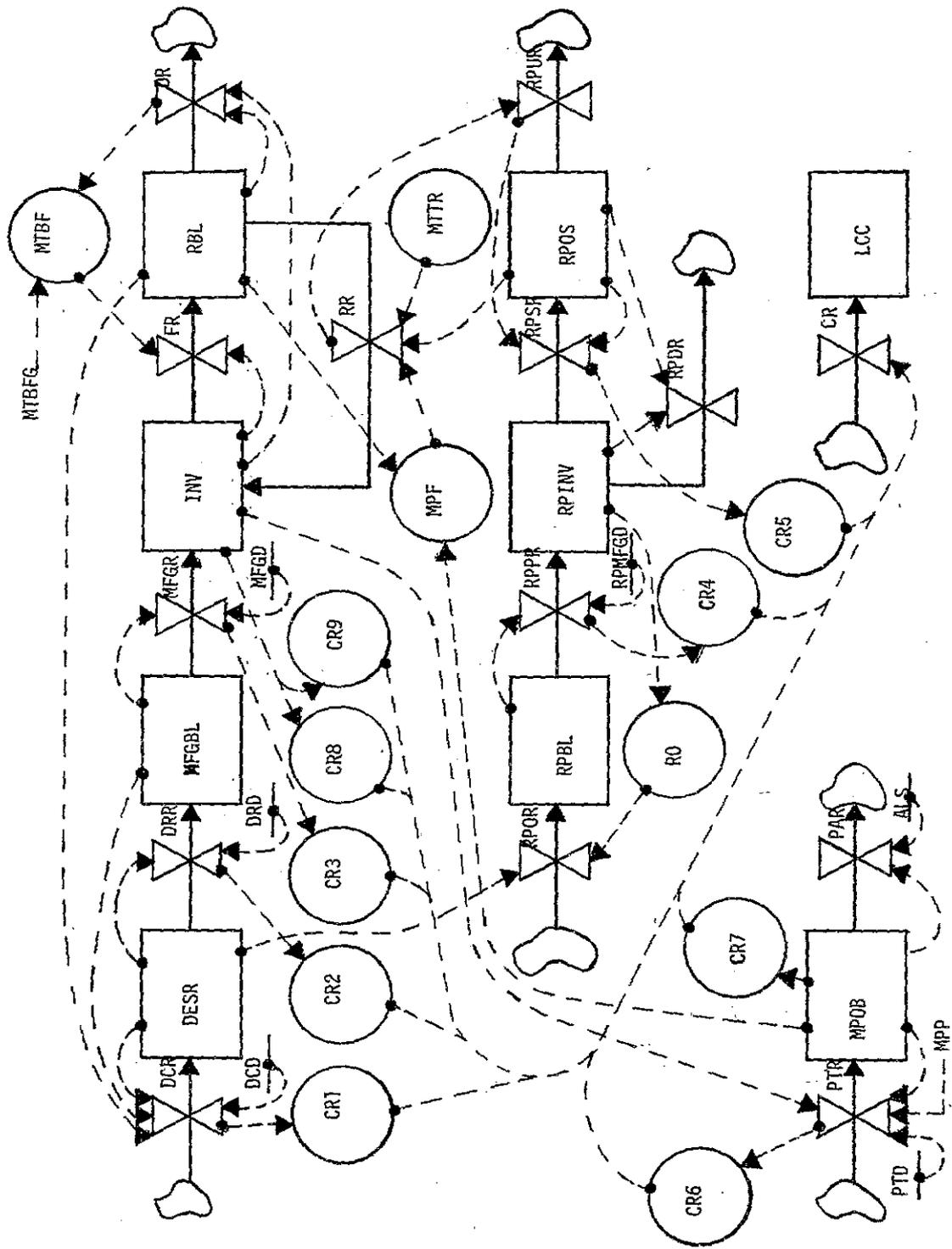


FIGURE 1. COST OF OWNERSHIP FLOW BLOCK DIAGRAM

The repair parts sector models the flow and control of repair parts in the system. Initial outfitting and reordering policies can be set. Costs are accumulated for the acquisition and replenishment of repair parts based on policy and use rate.

The final sector in the system is the personnel sector. The personnel flow consists of the training of maintenance personnel. A decision factor would be the establishment of personnel levels. A refinement of this sector of the flow chart would include a feedback loop from the repair time. As repair backlog is reduced because of improved design, better documentation, and improved diagnostic techniques, personnel levels would be reduced. The maintenance personnel level consists of both preventive and corrective maintenance tasks. Only the portion relating to corrective maintenance is considered in this model as effecting the repair rate.

Although the overall model has a number of simplifying assumptions, the essential elements which generate costs are included. The decisions can be altered to obtain sensitivity data relating to the influence of decision on design/logistics alteration. This in turn will lead to optimum design/logistics trade-off decisions in the formulative stages of the development cycle where they can be easily implemented.

Assembly Sector. The assembly sector is modeled by four levels, or state variables. The simulation is initialized with Design Remaining (DESR)=100%. As Design Change Rate (DCR) drains into Manufacturing Backlog (MFGBL), a conversion factor of 10 is introduced to effectively manufacture 1,000 assemblies (or module boards). These assemblies are manufactured at the rate MFGR and delivered to the user's inventory (INV). When there are at least 900 assemblies in INV, the trainer is operational. The remaining 100 assemblies become the on-board spares. As the trainer is operated, assembly failures occur at some failure rate (FR). When assemblies fail, they enter the repair backlog (RBL). The repair rate (RR) is constrained by the number of maintenance personnel on board and the number of repair parts on site. After faulty assemblies are repaired, they cycle back into the inventory. At any point in time, if the repair backlog exceeds 100 assemblies, a design change is implemented which is modeled by increasing DESR from its present value. This causes additional design and manufacturing efforts to be expended. The point in time when the redesigned assemblies enter the inventory is sensed and a comparable number of old

assemblies are disposed. Also when the new assemblies enter the inventory, the failure rate is automatically adjusted accordingly. While the trainer is operated and necessary repairs are effected, the maintenance personnel become more proficient. To account for this common situation, the repair rate is implemented as a monotonically increasing function of time.

The DYNAMO statements for the assembly sector are:

NOTE ASSEMBLY SECTOR

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N DESR=100
R DCR.KL=0.1*CLIP(RBL.K-10*DESR.K,0,RBL.K,
  100)*SWITCH(1,0,MFGBL.K)*CLIP(1,0,RBL.K,
  10*DESR.K)/DCD
L DESR.K=DESR.J+DT*(DCR.JK-DRR.JK)
R DRR.KL=10*DELAY3(DESR.K,DRD)
C DCD=12
C DRD=24
L MFGBL.K=MFGBL.J+DT*(DRR.JK-MFGR.JK)
R MFGR.KL=DELAY3(MFGBL.K,MFGD)
C MFGD=48
L INV.K+INV.J+DT*(MFGR.JK+RR.JK-FR.JK)
R FR.KL=(INV.K/MTBF.K)*CLIP(1,0,INV.K,900)
A MTBF.K=MTBF.J+0.25*(MTBF-MTBF.J)*SWITCH
  (0,1,DR.JK)
L RBL.K=RBL.J+DT*(FR.JK-RR.JK-DR.JK)
R DR.KL=CLIP(1,0,INV.K+RBL.K,1000)*CLIP
  (RBL.K,INV.K+RBL.K-1000,INV.K+RBL.K-1000,
  RBL.K)
A MPF.K=CLIP(MTTR.K*MPOB.K,RBL.K,RBL.K,
  MTTR.K*MPOB.K)
R RR.KL=CLIP(MPF.K,RPOS.K/25,RPOS.K/25,
  MPF.K)
A MTTR.K=TABHL(MT,TIME,0,156,52)
T MT=5/5/7.5/10

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Repair Parts Sector. The repair parts sector is modeled by three levels which are very similar to those of the assembly sector. When DESR drains into MFGBL in the assembly sector, repair parts are ordered and the repair parts backlog (RPBL) grows. These are produced at some rate (RPPR) and enter the repair parts inventory (RPINV). A maximum stock level replenishment policy was implemented for the repair parts inventory. From RPinV repair parts are shipped to the trainer site and enter the on-site inventory (RPOS). Replenishment of RPOS utilizes forecasting for a four week period based on the current usage rate. Design changes in the assembly sector also affect the repair parts sector; for example, use of a more reliable transistor. After the new repair parts are produced, the old parts, which they replace, are disposed of.

The DYNAMO statements for the repair parts sector are:

NOTE REPAIR PARTS SECTOR

A RO.K=CLIP(20000-RPINV.K,0,5000,RPINV.K)*
 SWITCH(1,0,RO.J)
 R RPOR.KL=RO.K+250*DESR.K
 L RPBL.K=RPBL.J+DT*(RPOR.JK-RPPR.JK)
 R RPPR.KL=RPBL.K/RPMFGD
 C RPMFGD=4
 L RPINV.K=RPINV.J+DT*(RPPR.JK-RPSR.JK-
 RPDR.JK)
 R RPSR.KL=CLIP(RPINV.K+RPOS.K-25000,0,
 RPINV.K+RPOS.K,25000)
 L RPOS.K=RPOS.J+DT*(RPSR.JK-RPVR.JK)
 R RPUR.KL=25*RR.JK

Maintenance Personnel Sector. The maintenance personnel sector is modeled as only one level. Maintenance personnel on-board (MPOB) is a constraining factor for assembly repair rate. The maintenance personnel policy (MPP) determines the desired number of maintenance personnel. To assure an initial staffing of maintenance personnel when the trainer is first operational, the maintenance personnel training rate (PTR) is set equal to MPP when INV equals 200 assemblies. Due to personnel attrition rates (PAR), the number of maintenance personnel on board is decreased. An information feedback loop is implemented in this sector to train new maintenance personnel to replace those lost due to attrition, automatically regulating MPOB=MPP.

The DYNAMO statements for the maintenance personnel sector are:

NOTE MAINTENANCE PERSONNEL SECTOR

C PTD=10
 C ALS=104
 C MPP=10
 R PTR.KL=CLIP(MPP-MPOB.K,0,INV.K,200)/PTD
 L MPOB.K=MPOB.J+DT*(PTR.JK-PAR.JK)
 R PAR.KL=MPOB.K/ALS

Cost Sector. The cost sector is modeled as one monotonically increasing level called Life Cycle Cost (LCC). The cost rate (CR) which causes LCC to increase is computed as follows:

$$CR = \sum_i CR_i$$

The CR_i are costs associated with actions or items from all other sectors in the model. Generally, rates determine a cost; however, some level variables may cause a cost to be incurred. For example, the inventory level (INV) generates a utilities cost for operation of the trainer when INV ≥ 900, and when INV < 900 a lost training time cost is generated due to the trainer being inoperable. The readability of the DYNAMO statements for this sector makes it unnecessary to elaborate on these cost conversion factors.

The DYNAMO statements for the cost sector are:

NOTE COST SECTOR

A CR1.K=2000*CDR.JK
 A CR2.K=500*DRR.JK
 A CR3.K=L)))*MFGR.JK
 A CR4.K=10*RPPR.JK
 A CR5.K=2*RPSR.JK
 A CR6.K=1350*PTR.JK
 A CR7.K=135*MPOB.K
 A CR8.K=CLIP(35,0,INV.K,900)
 A CR9.K=CLIP(3000,0,900,INV.K)
 R CR.KL=CR1.K+CR2.K+CR3.K+CR4.K+CR5.K+CR7.K
 +CR8.K+CR9.K
 L LCC.K=LCC.J+DT*CR.K

State Variable Method. We have, to this point, shown the ease of modeling complex dynamic systems by constructing a flow block diagram and writing DYNAMO statements directly from this diagram. The obvious next step would be to run the DYNAMO program on a computer. However, a DYNAMO simulation package must be available to directly implement the DYNAMO program. If DYNAMO is not readily available, the DYNAMO statements are directly translatable into a state variable model (7). The state variable method is recognized to be a powerful technique for describing the behavior of dynamic systems. In general, the state variable method is concerned with solving equations of the form $\dot{x}(t) = f(x, u, t)$ where x is a vector of status (or state) variables and u is a vector of forcing functions. In the case of linear systems (and some nonlinear systems) this reduces to the form $\dot{x} = Ax + Bu$ where A is called the system matrix and B is the input distribution matrix. Normally, u is "absorbed" into x if \dot{u} is known. Then the augmented system matrix equation has the form $\dot{x} = A'x$ where A' now is the augmented system matrix and x is expanded to include u . The solution to the augmented system equation is simply $x(t) = e^{A(t-t_0)} x(t_0)$. The actual computer simulation of such a system is quite simple.

A sample time T is selected and a Taylor series expansion for e^{AT} is evaluated. This is called the state transition matrix. Then the state of the system is calculated at integer multiples of T as follows:

$$\begin{aligned} x(T) &= e^{A_0 T} x(0) \\ x(2T) &= e^{A_1 T} x(T) \\ &\vdots \\ x(N+1)T &= e^{A_N T} x(NT) \end{aligned}$$

Similarly for nonlinear systems, a piecewise linear approximation is formulated.

The transformation of DYNAMO statements into a state variable model can be accomplished by the following procedure. It is first noted that the DYNAMO level variables are system status variables. An equation of the form

$$\frac{d}{dt}(\text{level}) = \text{rate}_{\text{in}} - \text{rate}_{\text{out}}$$

can be written from each level equation. The DYNAMO rate and auxiliary equations describe the interrelationship of levels (state variables) and permit the above differential equation to be written in terms of other level variables. By following this simple procedure the DYNAMO model can be transformed into a state variable model of the form $\dot{x} = Ax + Bu$ where A, B, x and u are as described above.

Alternative Implementation Techniques.

The previous discussion of state variables was provided to demonstrate the ease of converting DYNAMO statements into other forms suitable for digital computer implementation and simulation. There are numerous other simulation techniques in existence. Availability of computer resources and range of applicability are constraining factors for determining which simulation technique to employ for a given model. For example, DYNAMO was not available at NAVTRAEQUIPCEN and the model described herein contains both continuous and discrete elements. The state variable model is inefficient when it encounters discrete switching functions. The system matrix changes, thus requiring re-evaluation of the matrix exponential. GASP IV, a FORTRAN based simulation language which permits a mixture of continuous and discrete entities, was selected for implementation of this cost of ownership model. Mr. E. S. Psarakis of the Data Services Center at NAVTRAEQUIPCEN is responsible for the development of this GASP IV model which should be operable prior to the Seventh NAVTRAEQUIPCEN/Industry Conference, November 1974. To demonstrate model utility, Mr. Psarakis will generate cost data, via the GASP IV model, to aid the management policy decision of optimally balancing design and maintenance efforts.

TABLE 1 - SYMBOL DIRECTORY

ALS	Average length of service
CR	Cost rate
DCD	Design change delay
DCR	Design change rate
DESR	Design remaining
DR	Disposal rate
DRD	Drawing release delay
DRR	Drawing release rate
FR	Failure rate
INV	Inventory
MFGBL	Manufacturing backlog
MFGD	Manufacturing delay
MFGR	Manufacturing rate
MPF	Maintenance personnel factor
MPOB	Maintenance personnel on board
MPP	Maintenance personnel policy
MTBF	Mean time between failure
MTTR	Mean time to repair
PAR	Personnel attrition rate
PTD	Personnel training delay
PTR	Personnel training rate
RBL	Repair backlog
RO	Replenishment order
RPBL	Repair parts backlog
RPDR	Repair parts disposal rate
RPINV	Repair parts inventory
RPMFGD	Repair parts manufacturing delay
RPPR	Repair parts production rate
RPOR	Repair parts order rate
RPOS	Repair parts on site
RPSR	Repair parts shipment rate
RPUR	Repair parts use rate
RR	Repair rate

REFERENCES

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MR. VINCENT AMICO is Director of Engineering at the Naval Training Equipment Center. He graduated from New York University with a Bachelor of Aeronautical Engineering in 1941. He was awarded a Masters in Business Administration from Hofstra College in 1954 and a Master of Science in Engineering from Florida Technological University in 1973. Mr. Amico worked on the design of naval aircraft as a stress analyst and project stress engineer with the Curtiss-Wright Corporation from 1941 to 1945. He entered the Armed Forces in 1945 and was assigned to the Static Test Unit of the Structures Laboratory at Wright Field as a structure research engineer. Upon leaving the service in 1947, Mr. Amico joined Republic Aviation Corporation with responsibility for preliminary design of missile and advanced aircraft systems. He joined the Center in the fall of 1948 as a project engineer in the Flight Trainers Branch. Since then he has progressed through the engineering organization to his present position. During this time, he was responsible for the development and production of a wide variety of training devices in all warfare areas. Mr. Amico is a member of Tau Beta Pi and Alpha Pi Mu Honorary Engineering Fraternities, American Society of Military Engineers, Society for Experimental Stress Analysis, Research Society of America, Sigma Xi, the American Institute for Aeronautics and Astronautics, and the Armed Forces Communications and Electronics Association. He was past Chairman of the New York section of the Institute of Aerospace Science and the Orange Chapter of the Armed Forces Communications and Electronics Association. Mr. Amico holds two patents and has presented a paper to the Institute of Radio Engineers on Synthetic Training for Space Flight.

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