PROJECT WISH:
THE EMERALD CITY

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Abstract

Phase III of Project WISH saw the evolution of the Emerald City (E-City) from a collection of specialized independent analyses and ideas to a working structural design integrated with major support systems and analyses. Emphasis was placed on comparing and contrasting the closed and open cycle gas core nuclear rocket engines to further determine the optimum propulsive system for the E-City. Power and thermal control requirements were then defined and the question of how to meet these requirements was addressed. Software was developed to automate the mission/system/configuration analysis so changes dictated by various subsystem constraints could be managed efficiently and analyzed interactively. In addition, the liquid hydrogen propellant tank was statically designed for minimum mass and shape optimization using a finite element modeling package called SDRC I-DEAS, while spoke and shaft cross-sectional areas were optimized on ASTROS (Automated Structural Optimization System) for mass minimization. A structural dynamic analysis of the optimal structure also conducted using ASTROS enabled a study of the modes, frequencies, displacements, and accelerations of the E-City. Finally, the attitude control system design began with an initial mass moment of inertia analysis and was then designed and optimized using linear quadratic regulator control theory.

Introduction

Project Wandering Interplanetary Space Harbor (WISH), a three-year advanced design project at the Ohio State University, began as a possible follow-up to the current Space Exploration Initiative (SEI) program set forth by President Bush and NASA. The goal of Project WISH is to design conceptually a spacecraft to be used in the exploration of the solar system during the mid-21st century. This design entails a Permanently Manned Autonomous Space Oasis (PEMASO), designated the Emerald City (E-City), with a mission to support colonization and exploration efforts throughout the solar system. Home to 1000 colonists, the E-City must have the capability to re-station itself almost anywhere in the solar system within a transit time of three to five years. Envisioned to become operational in the year 2050, PEMASO must be self-sufficient, requiring no additional resources from Earth once deployed. Based on the SEI time line, by the middle of the 21st century, humans should be firmly established on the moon and Mars, and a great deal of experience in working and living in space will have been accumulated. At a nominal orbit of four Astronomical Units (AUs), the E-City will be in an ideal location to mine the asteroids for natural resources as well as to obtain hydrogen from Jupiter's atmosphere.

Phases I and II of Project WISH established the groundwork for Phase III and were conducted during the 1989-1990 and 1990-1991 academic years. Phase I encompassed a general level study of the major systems required for the E-City while Phase II completed a more in-depth study into the disciplines of orbital mechanics, propulsion, attitude control, and human factors. Guidelines were also established for the design of the ship and were used to carry out two particular missions of interest: a Saturn Envelope mission and an Earth-to-Mars mission.

Phase III Project WISH (Figure 1) saw the evolution of the E-City from a collection of specialized independent analyses and ideas to a working structural design integrated with major support systems and analyses. Optimization and system integration were key in establishing the final design parameters. Detailed analyses and studies were conducted in propulsion, power and thermal control systems, mission/ system/ configuration design, static and dynamic structures, and attitude control.

Propulsion

The propulsion system is one of the most challenging design aspects of Project WISH in terms of the performance requirements it needed to achieve. Achieving total delta-V's ranging from 50-100 km/sec as a propulsion capacity is no easy task.

Throughout the three-year period of Project WISH, feasibility studies of several conceptual propulsion systems have been performed. The Phase I design team had analyzed chemical, nuclear, and anti-matter rocket engines before recommending anti-matter as the most probable system. The Phase II design team, reconsidering that the anti-matter engine was too conceptual in nature for the time frame of Project WISH, proposed to use a gas-core nuclear rocket engine, the space radiated gas core nuclear rocket (SRGCNR), or open-cycle engine. The Phase II team had hoped that the high specific impulse it generated and its projected technological feasibility engine would prove satisfactory to the needs of E-City. However, due to hazardous radiation emitted from the exhaust plume and high mass penalty associated with these engines, it was decided to reconsider once more the system used for main propulsion.

The open-cycle engine operates by using fissioning gaseous uranium to transmit thermal energy to a hydrogen propellant. The hydrogen is then exhausted out the nozzle at high speeds. The advantage of this engine is the high value of specific impulse that it can generate. Specific impulse is a measure of the amount of momentum transfer per unit weight of propellant. The higher the specific impulse, the less propellant that is needed to achieve a certain velocity. Since the open-cycle can produce specific impulse values within the range of 2000 - 6000 seconds, the Phase II team felt that this engine was sufficient for E-City.

The open-cycle engine has two serious drawbacks, both of which are related. Because the uranium is in contact with the hydrogen propellant, there is a loss of uranium out the nozzle. The Phase II team calculated that the amount of uranium loss would approach almost 2 metric tons per engine per day of operation. The second drawback is that the exhaust plume from this type of engine contains large amounts of harmful radiation. This results in excessive shielding required to protect the inhabitants of E-City.

Using the open-cycle propulsion system, the Phase II team had calculated that it would require at least 33 engines for a mission from Earth to Mars. A trip to Saturn would require 172! This also added to the mass of E-City. Still, because the specific impulse seemed to be the governing parameter for the propulsion system, these drawbacks were tolerated.

This year, in an effort to solve the plume radiation problem and reduce the mass of E-City, another type of nuclear rocket engine was studied. Known as the closed-cycle, or nuclear light bulb (NLB) engine, its nature of operation immediately solves problems associated with the open-cycle engine.

The NLB functions in much the same way as the open-cycle engine, except that the gaseous uranium is enclosed in internally cooled, transparent structures. Neon surrounds the gaseous core to separate it from the transparent enclosure and to attenuate the extreme temperature of the uranium. Thermal radiation from the uranium is transmitted through the neon and transparent structures to a seeded hydrogen propellant. The seeding is made up of microparticles of tungsten to help increase the amount of thermal energy transmitted to the propellant. Because the gaseous uranium does not come into contact with the propellant, the exhaust plume does not contain any harmful radiation.

The uranium and neon are part of an intricate closed-cycle system designed to keep the engine from overheating. Essentially, the hot gases are run through the turbopumps and heat exchangers to convert liquid hydrogen propellant into a gaseous state. The cooled uranium and neon are then recycled back into the system

EMERALD CITY
CONFIGURATION

Z

LIQUID HYDROGEN
PROPELLANT
TANK

LIQUID
OXYGEN
TANKS

TORUS

HUB

USA
E-CITY 3

X or Y

SHUTTLE

SPOKES

CONTROL
THRUSTERS

LIQUID HYDROGEN
PROPELLANT
TANK

BUBBLE
RADIATOR

MAIN ENGINES
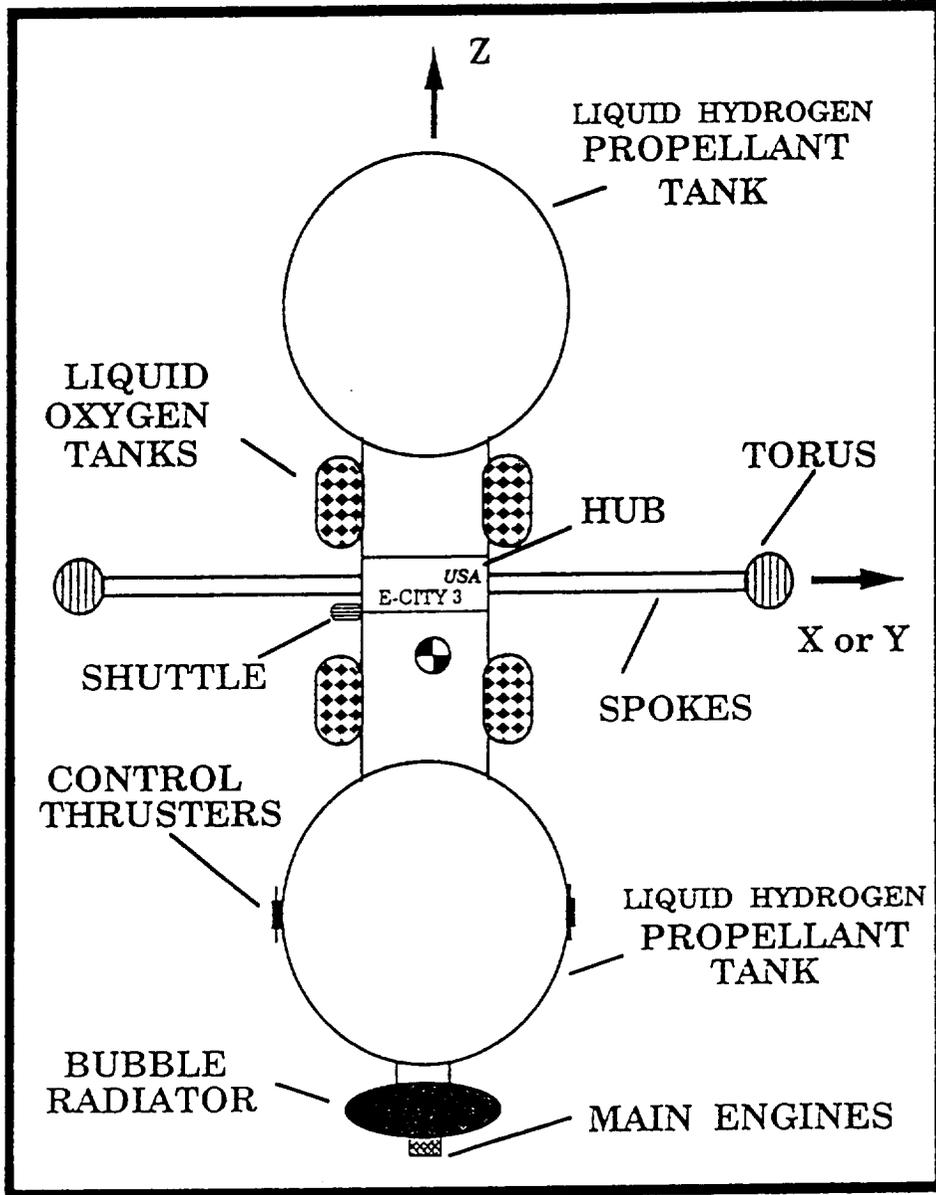
Fig. 1 Emerald City configuration

for further thermal control of the NLB. It is the closed-cycle process of the NLB that prevents uranium loss during operation.

The NLB does not generate as high a value of specific impulse as the open-cycle engine. However, the thrust it produces is ten times higher than that of the open-cycle. From this year's analysis, it was found that an increase in the thrust, and specifically the thrust-to-weight ratio, would dramatically reduce the number of engines required for a given mission.

With the radiation problem taken care of and the mass penalty reduced, it seemed that the use of the NLB engine as the main propulsive system was warranted. However, until an analysis was performed that directly compared the NLB to the open-cycle engine, a final decision on the best system for E-City could not be made.

Using the previous Project WISH reports and information provided by NASA Lewis Research Center, it was possible to achieve comparable results between the NLB and open-cycle engines. The information provided by Dr. Borowski contained performance parameters for seven experimental NLB engines. Some of these engine characteristics were engine thrust, uranium radiating temperature, specific impulse, and hydrogen propellant flow rate. By representing these parameters as a function of the radiating temperature, it was discovered that most of the NLB engine characteristics increased parabolically. The only exception was for specific impulse, on account of thermodynamic factors associated with NLB operation.

Through curve fit approximations of the data using a software package, it was possible to find any desired parameter as a function of the radiation temperature. Based on the functions generated by curvefitting, two FORTRAN programs were written expressly for the purposes of Project WISH.

The accuracy of the programs was checked with known data points supplied by Dr. Borowski. The average percent deviation was 0.59%, which proved that the curve fit functions were adequate for the purposes of Project WISH.

Performing the calculations necessary to determine the number of engines required for a given mission with a specific impulse of 3100 secs, thrust of 9.4 million Newtons per engine, and a thrust to weight ratio of 9.6 per engine, it was found that only one engine was required for a mission to Mars and the envelope mission to Saturn would require 14 NLB engines.

As expected, the NLB engine far exceeded the open-cycle engine in terms of performance requirements and projected available technology for E-City. Use of the NLB means that the plume radiation problem is eliminated. The fact that the number of engines required for a given mission is more than ten times less than an open-cycle system points to a further reduction in total engine mass. Based on the results of the analysis, the NLB engine is the recommended propulsive system for E-City.

Mission, System, and Configuration Design

Mission Profile

The Saturn envelope mission profile was chosen as the baseline because it has the most demanding performance requirements of all the feasible missions.[1] It requires a delta-V of 50 km/sec for transfer from the nominal orbit of 4 AU.

The primary objective of the structural design was to minimize the dry mass while fulfilling essential performance parameters. The driving factor determining the overall mass is the amount of propellant required for the mission. Equation 1 shows the relation between the dry mass and the propellant mass,

$$m_p = m_{dry}\left[\exp\left(\frac{\Delta V}{I_{sp}g} \right) - 1 \right] \tag{1}$$

The value of m_p/m_{dry} was 4.19 using a delta-V of 50,000 m/s and an I_{sp} of 3095 sec, which dramatically shows the impact of adding mass.

System Parameters

The computation of system parameters (masses, dimensions, forces, etc.) was automated so that the effect of changes in the configuration could be analyzed interactively. The 30 design variables that were used are those that affect the dry mass of the E-City.

The configuration of the E-City is the result of integrating the requirements dictated by a low mass, structurally sound design, good controllability, and minimum stress on the inhabitants. The inhabited and rotating torus section was found to be the most efficient geometry for the living space. Its dimensions were determined by human factors considerations studied in reference 1 on the Phase II design.

The closed-cycle nuclear engine allows minimization of the radiation shield to that required to protect the inhabitants from cosmic and solar radiation, and it surrounds the torus. It consists of 14 meters of liquid hydrogen contained in a separated pressure vessel, with a vacuum between it and the inhabited torus for enhanced thermal insulation.

The hydrodynamic effort of tank rotation is a potentially more serious problem, and is caused by a radial acceleration (caused by rotation) that is up to 100 times greater than the longitudinal acceleration (from thrust). At some point the tank will effectively "run out of gas" because the propellant is forced away from the main feed orifice (drain) and against the wall. If there is no thrusting, the propellant will pile up along the walls with a tube of gas running down the centerline, and none of the LH_2 will reach the drain, even with full tanks.

The number of tanks used in the final design will not depend on the total tank mass. Software[2] was developed to compare the total mass and total surface area for various aspect ratios and numbers of tanks. Studies show that the total mass decreased as the number of tanks was increased. On the other hand, the total surface area increased. This comparison also conclusively showed that a sphere was the most optimum shape for the tank configuration regardless of the number of tanks used.

The primary disadvantage of one tank is the potential loss of the entire propellant load due to tank failure, whether caused by collision or random failure. Redundancy was the primary consideration in dividing the propellant load into two tanks.

Structural Design

Static Structure

The static structural analysis played a pivotal role in the design of the E-City. It was used as the initial basis for the determination of cross-sectional areas and other dimensions, which were then analyzed as a whole for the dynamic behavior of the entire vehicle. Those areas that needed further modifications to meet structural dynamic criteria were then treated and allowances made for the required modifications. The majority of the static structural analysis was included in a parameters program,[2] since the overall mass was related to the component dimensions and their densities.

Propellant Tanks

It was the intent of this design effort to optimize the tank configuration so that the total mass was minimized. Since the tank is the single largest component on the E-City, mass minimization was essential to gain the highest performance possible. Pressure vessel theory is fine for determining the overall stress characteristics of the propellant tank, but is inadequate for pinpointing stress concentrations due to the combined loads of thrusting, rotation, and pressure.

The models were created on I-DEAS utilizing the symmetry of the tank to reduce the size of the model and the number of elements in the finite element model. A benefit of this method of modeling was to reduce the computing time necessary to solve the finite memory required to execute the mesh solver.

Initially the tank structure was optimized, maintaining a constant volume and using only the pressure forces in an attempt to obtain a uniform stress pattern. Considering the magnitude of the thrusting forces, the best approach to obtain the optimum configuration was to initially design only for the pressure forces. Once this was completed, the thrusting force effects would be analyzed. Another advantage to this approach is that the I-DEAS results could be compared and verified with thin pressure vessel theory.

Once the structural configuration was finalized, optimization of the wall thickness was then performed to achieve a maximum principal stress equal to the working

stress of the aluminum, 165 MPa with a factor of safety of 1.5. Analyzing the effect of the thrusting forces and their effect on the design of the tank concluded the stress analysis.

Stress analyses were performed on several models covering various height to diameter aspect ratios (ARs) in order to achieve the optimum structural tank shape. The initial model consisted of a cylindrical tank with hemispherical end caps with an AR of 6, corresponding to a height of 1845 m and radius of 154 m.

Based on the results of this analysis, it was shown that the optimum configuration for the tank is, in fact, a sphere and not a cylinder. This agrees with thin pressure vessel theory.

In an effort to create a finite element model that would correctly represent the actual tank, a 3-D model was generated. Initial analyses were performed using internal pressure only to obtain the optimum tank wall thickness, as stated previously. Internal pressure was applied using the face pressure option on I-DEAS.

Comparing the mass of the original tank with an aspect ratio of six, 99.137 MKg, with the optimized spherical tank mass of 71.696 MKg showed a mass saving of 27.7%. This also produced a significant saving in propellant mass. Optimizing the cylindrical tank to a spherical tank also yielded a significant reduction in surface area of 31.4%, especially important from a heat transfer point of view.

In the next case the thrusting forces were applied to the previous tank configuration. As this was only a quarter of the tanks, only 25% of the total thrusting forces were applied to the bottom centerline nodes. The stress patterns were nearly identical to those observed for the same model under pressure forces only. The maximum principal stress increases to 516 MPa, which, again, is concentrated at the top and bottom nodes along the centerline. If only the stresses in the center portion of the tank are considered, they range from 200 to 275 MPa, which is significantly larger than the 165 MPa working stress. The maximum displacement profile for this case was 3.11 m. An actual tank could fail due to exceeding the 248 MPa maximum stress of aluminum.

The analysis of the spherical tank consisted of finite element modeling of the pressure vessel to determine the

locations of any stress concentrations using I-DEAS. The objective of the analysis was to determine the optimal placement of the supports to minimize the amount of reinforcement that would be needed. The initial assumption used for the thickness of the tank was based on thin pressure vessel theory:

$$\sigma = pr/2t \qquad (2)$$

where σ is the stress, p the pressure inside the tank, r the radius of the tank, and t the thickness of the tank wall.

The thickness of the tank was .0141 meters using a working stress of 165 MPa for the aluminum alloy selected, with a pressure of 0.2 atm (20265 Pa) and a radius of 230 meters. The radius used was about 5% larger than necessary for the initial configuration to give conservative results.

The stresses and deflections reached acceptable values when the tank supports were moved out sideways. Even though the applied forces at burnout were twice as high as during the initial acceleration, the stress contours were nearly identical, which implied that the tank pressurization was the dominant force.

Torus

A torus was determined to be the most efficient shape for the crew living quarters by the Phase II design team. It is designed as a totally enclosed ecological system, with energy as its only input after the Biosphere II Project.[1] Volume requirements were set at 19,000 cubic meters per person to allow extra space for manufacturing, food processing, and other as yet unconsidered needs. It will be constructed of aluminum alloy and sized so that rotation will provide one-g of artificial gravity. Current dimensions include a major radius of 894.6 meters and a minor radius (tube) of 322.8 meters. The pressure of the enclosed atmosphere was set to 1 atm and of the same composition as that of each to minimize the long-term impact on the inhabitants since little is known of such long-term effects.

The most efficient cosmic radiation shield was determined last year by the Phase II design team to be 14 meters of liquid hydrogen. It was determined that the shield must rotate with the torus. The spinning shield was required because there was no apparent failsafe method

to maintain separation between the torus and shield during maneuvering. The torus rotates with a linear velocity of 97.1 m/s and any mechanism to maintain separation induces potentially unacceptable vibrations in the torus and dissipates rotational energy. The difficulty in maintaining separation is exacerbated by the vibration mode shapes induced by thrusting. A failure of the mechanism separating the rotating torus and stationary shield could have catastrophic consequences, and no viable alternatives were discovered to alleviate this problem; therefore the shield must rotate with the torus.

The spokes are the only interface between the crew quarters and the mechanical subsystems of the E-City. They act as cantilever beams and transmit the thrusting forces to the torus and cosmic radiation shield. The shaft is the central connecting structure for the tanks, propulsion module, and torus coupling. The primary force on the shaft is due to the axial thrusting load. In this case the bending moment was assumed to be negligible compared to the axial pressure during thrusting and was used to develop the preliminary estimate of the cross-sectional area. The radius was determined by the optimal placement of thrusting loads on the tanks.

The majority of the static structural analysis was performed by a computer program developed to provide interactive parameter analysis. Using software also reduced the second design iteration to one day as the

program reached maturity. A spherical propellant tank provided the optimum configuration with the lowest mass and lowest surface area. Some optimization of the tank wall thickness was provided by calculating the thickness in sections. The minimum mass tank configuration was obtained by transmitting the thrusting loads through the tank walls without the addition of special supports or reinforcements. The mass of the spokes and shaft were computed using simplified formulas as starting values for optimization using ASTROS.

Structural Dynamics

A dynamic analysis is necessary for a complete evaluation of the E-City. The modes, frequencies, displacements, and accelerations of the E-City are needed for the design of the subsystems. Humans inhabiting the torus should not be subjected to intense acceleration, and certain frequencies that are resonant to the various subsystems must be avoided. In addition, structural mass should be minimized, yet not fail when the E-City is under the influence of external loads.

The dynamic analysis was carried out using the Finite Element Method. To perform the finite element analysis on the E-City, the software package ASTROS was employed. ASTROS is similar to NASTRAN and also has the capability of optimizing a model for a minimum mass configuration, a feature used in later analysis.

Table 1 Results of static shaft and spoke optimization

	Shaft		Spokes	
	Initial	Optimized	Initial	Optimized
Cross-sectional area (m2)	6.28625	1.13964	12.59779	0.12560
Wall thickness (m)	0.01000	0.00181	0.10000	0.00010
Mass per element (*1000 kg)	333.17	60.40	7469.70	74.47
Initial structural mass (torus, spokes, shaft)	367 610 000 kg			
Optimized structural mass	187 397 000 kg			
Percent reduction	49.0%			

The finite element model utilizing bar elements with six degrees of freedom each has six spokes with four elements, each having a 20m radius; a 24-element torus with a 35-m tube radius; and a 200-m-long shaft with ten elements, each having a 100-m radius. The total finite element model had 318 degrees of freedom. The optimization feature of ASTROS was used to minimize the total masses of the shaft and spokes subject to Von Mise's yield criterion under static axial thrust loading.

The initial wall thickness of the shaft was 10 mm and 100 mm for spokes. After optimization, these were reduced to 0.29 mm and 1.00 mm, respectively. The torus was not optimized due to some computational limitations encountered in the software. The designed structural mass of the shaft and spokes was reduced from 2.2794 billion kg to 0.00239 billion kg. Table 1 shows the results of the static optimization.

The statically optimized structure was dynamically analyzed by ASTROS under the modes discipline with the output being the natural frequencies and modes of vibration of the system. The modes were illustrated visually through the use of the graphics package PATRAN, and the significant modes were identified to study the axial vibrational dynamics due to thrust loads.

The out-of-plane motion of the torus is of significance for crew comfort since it will result in lateral swaying motion of the living quarters. It was decided to study this motion so that displacements and accelerations due to thrust loading on the statically optimized design could be defined. Therefore, only the symmetric torus modes with significant axial displacements were taken into account in the modal axial dynamics. Three such modes were chosen for a reduced-order model of the axial dynamics. Table 2 identifies these modes. The next step was to simulate the reduced modal dynamics due to thrust loading which requires a state-space formulation of the equations of motion. The problem was programmed via the PRO-MATLAB software, and the displacements and accelerations at each grid point in the axial direction were determined. It was found that maximum vibrational displacement of typical torus points for the optimized design, discussed in the previous sections, would be about 8 m at the beginning of the thrusting period and would reach six times this value at the end of the thrusting period when the fuel tanks are empty. Thus the analysis established the need for further design for active and/or passive control of structural vibrations.

Table 2 Modes selected for study of axial dynamics under thrust loading

Mode #	Mode Description	Frequency		Period
		rad/s	Hz	(sec)
16	Rigid torus	0.030760	0.00490	204.29
19	Rigid torus	0.101903	0.05081	19.68
22	Ruffle torus	0.155079	0.06267	15.96

Attitude Control System Design

Subject to altering disturbances which must be controlled, a Mass Moment of Inertia (MMI) analysis of the E-City is required to study the vehicle's stability and control characteristics. The MMI study is essential to Project WISH's attitude control system optimization. Modeling E-City as a rigid body consisting of lumped masses, Phase I established the basis for a MMI study. The work in the previous two years focused on obtaining an order of magnitude estimation of the MMIs, and the whole ship was modeled as spinning.

Phase II emphasizes a more rigorous approach to the ship's configuration, which includes a more accurate and complex MMI analysis. This year's work was devoted to a dual-spin configuration which requires that only the torus and spokes rotate about the spin axis. Developing a reliable and user-friendly FORTRAN program to calculate the MMIs of an evolvingly complex E-City structure is the motivation behind Phase III of the dual-spin MMI analysis. Accurately calculating the MMI ratios required by an ensuing attitude control study and defining the ship's structure were the goals.

To calculate two MMI ratios which are required for the attitude control analysis, the following ratios were used:

$$r1 = Izspn/Ix \qquad (3)$$
$$r2 = Ixspn/Ix \qquad (4)$$

in which Izspn is the sum of the torus and spokes MMI component about the spin axis, Ixspn is the sum of the torus and spokes MMI about the x or y axis, and Ix is the ship component about the x or y axis. Because of the axial symmetry about the z axis, the center of mass (CM) will lie on the z axis. Its location, denoted by Zcm, is designed as the displacement of the mass center from the torus center.

Since this was a configuration consisting of many components, the Parallel Axis Theorem must be incorporated to transfer each component's MMI with respect to the CM location. This component is then added to each component's individual MMI to obtain a total contribution. Finally, the two ratios r1 and r2 were obtained, and the attitude control design was initiated.

The attitude dynamics of the E-City were studied in Phase I of Project WISH, during which the stable configurations of the spacecraft were determined. A study conducted during Phase II determined the state response due to initial disturbances and the attitude control design requirements needed to damp out these disturbances. In Phase I the entire E-City was assumed spinning.

Due to the dual-spin nature of the E-City and the configuration changes that took place in Phase III of Project WISH, the attitude control design needed to be reassessed. The objective in Phase III was to control effectively,and in a manner acceptable to the crew, the gyroscopic wobble of the station following a disturbance. This included optimizing the number of control clusters, the number of thrusters per cluster, the propellant mass requirements, and the control power required.

To begin the study, it was assumed that the control thrusters would be placed in clusters evenly distributed around the main propellant tank. Next the torque on the spacecraft was determined in matrix form using the selected configurations. This torque matrix was non-dimensionalized and substituted into the non-dimensional gyroscopic state equation of a dual-spin body, given by:

$$\hat{\dot{X}} = [A][\hat{X}] + [B][\hat{T}] \qquad (5)$$

where X is the state of the system model, T is the torque matrix, and A and B are matrices defined in Ref 2. The A matrix is dependent upon the MMI ratios established in the MMI analysis. The linear quadratic regulator control theory was used to obtain the state response that minimized the control design performance index, given by:

$$CDPI = \frac{1}{2} \int_0^\infty \left(wx\hat{X}^T\hat{X} + wc\hat{T}^T\hat{T} \right) d\tau \qquad (6)$$

where wx is the state weighting and wc is the control weighting parameters, respectively.

By using the control law obtained from the minimization of CDPI, designers used the following equation to determined the non-dimensional control power:

$$S^* = \int_o^\infty \hat{T}^T \hat{u} -^T \hat{u}^{-1} T d\tau \qquad (7)$$

where $\hat{u} = D_t^{-1}[D]$

The D matrix is a non-dimensional thruster distribution matrix related to the thruster configuration placement. The root-mean-squared power required to damp out an initial disturbance is then found from

$$P_{rms} = (v_{ex}I_x n^2/2D_t)^* sqrt(S^*/\tau_c) \qquad (8)$$

where n is the spin rate of the torus in rad/sec, I_x is the moment of inertia of the ship about the x-axis, v_{ex} is the exhaust velocity of the control thrusters, and τ_c is the non-dimensional control time.

To reduce the amount of power required for control, the number of clusters was computed against P_{rms} for various weighting parameters, wc and wx, and several initial disturbances. The results were used to determine the optimal number of clusters.

After this was accomplished, the state response due to an asteroid impact was modeled to determine its effect on the E-City. Two cases were evaluated assuming perfectly plastic collisions: a head-to-head collision and a tail-to-tail collision. This analysis was done to quantify what the chosen initial disturbance would "feel like" to the ship and what this would represent in physical terms.

Determining the acceleration levels experienced by the crew due to gyroscopic attitude dynamics was the next step in the control optimization process. Through this analysis, the number of thrusters in each cluster, propellant mass per control effort, maximum thrust per cluster, settling time, the state weighting wx, and the control weighting wc were determined. The primary constraints based on human factors were the lateral swaying acceleration felt by the crew while moving onboard and the settling time. It was desired that this acceleration disturbance would immediately settle to zero after the initial disturbance without overshoot.

The acceleration levels were determined for a person running in the spin direction of the torus. This would be the direction for which the crew would experience the highest g levels. The weighting parameters wc and wx

were then varied to determine the control settling time, propellant mass, maximum thrust, and acceleration level profiles. Various design parameters were then studied against values of wc for a specific wx. Several iterations were completed to determine the patterns for the various parameters in relation to increasing or decreasing weighting parameter values. Results of attitude control system optimization are listed in Table 3.

Table 3 Attitude control results

Thrust available/engine	2.58 million (N)
Isp/engine	437 sec
Control power required	722 billion Watts
Maximum thrust/cluster	289 million (N)
Number of engines/cluster	112
Control propellant	32.1 million (kg)
wc (control weighting)	640
wx (state weighting)	375
Number of thruster clusters	50

Power and Thermal Control System

Power System

The E-City is composed of numerous subsystems that will require electrical and/or thermal energy to operate properly. The primary concern of the power system is to supply continuous energy to each of E-City's subsystems for as long as necessary to complete a given mission. The thermal control systems must be able to dissipate the waste heat generated by the various power devices on board.

A rotating particle bed reactor capable of generating a maximum of 5000 MWth is sufficient to supply power to E-City. A converter coupling network is required, which is essentially a switch that channels the thermal energy from the reactor to either the magnetohydrodynamic (MHD) or thermoelectric converter. During normal operation, the thermal energy is channeled completely through the highly efficient MHD converter. In an emergency situation, the thermal power can be redirected to the thermoelectric converter as a type of backup system. The usable electrical power generated by the converters is sent to the power coupling network. The remaining unconverted thermal energy, referred to as

waste heat, is dissipated by sending it to an external radiator.

The power coupling network is responsible for supplying power to the propulsion, attitude and control, heat transfer, and ship operations systems. Depending on the operating mode of the ship this network is responsible for supplying the appropriate amount of power to each system. It also serves the purpose of redirecting power to systems in emergency situations.

From the power coupling network, the usable power is distributed to the four major systems of E-City. The propulsion and attitude control systems need start-up power only. The heat transfer subsystems require power to either actively and/or passively dissipate the waste heat created by all the power generating devices of E-City. The systems required for navigation, life support, communications, shuttle and maintenance, and other miscellaneous tasks must receive power for all phases of E-City's operation.

Once the power system was established, the next step was to envision typical operating modes of the ship. These operating modes would be based on the startup, burn time, and shutdown of the engines and/or attitude and control thrusters.

The start-up procedure is essentially a type of chain reaction sequence. The rotating particle bed reactor can supply only 5000 MWth for starting up the engines. This is enough power to start only one NLB engine. It would be highly impractical to add 13 more particle bed reactors, simply to start the remaining engines.

Using the fact that an NLB engine is a power generating device in itself, it does not seem unlikely that one modified NLB engine could generate power to start the remaining engines. This modified engine, referred to as the start-up engine, would possess some type of moderator/thermal energy network. This network would be capable of using the energy output from the start-up engine to start the remaining engines.

There are two start-up phases. The first start-up phase refers to the rotating particle bed reactor generating 4800 MWth to start a fission reaction in one NLB engine. The second phase startup refers to the startup engine supplying power to start the rest of the engines.

Once the engines and thruster are operating, they no longer need any external power source. Minimal power for systems monitoring engine and thruster status are needed for propulsion and attitude control. The only systems requiring power are heat transfer and ship operations.

The shutdown of the main engines is a crucial operating mode for E-City. It entails powering down the main engines by terminating the fission reaction occurring within them.

The fifth and final operating mode of E-City takes place when the burn time for the mission has been reached, and the main engines are shut down. At this time, unless E-City is utilizing NLB engines as attitude control thrusters, the particle bed reactor needs only to supply power to ship operations.

Thermal Control

Thermal control systems can be characterized broadly into two categories: active and passive. This study defines active systems as those required to dissipate internally generated heat and passive systems as those required to isolate the station from external heat sources. Basic heat exchange equations were used along with several simplifying assumptions to create the thermal model of the E-City.

The most critical portions of the E-City needing passive control of heat transfer are the hydrogen propellant storage tanks. The only external heat source considered was solar radiation. The intensity of solar radiation decreases exponentially with distance, so only the worst case of a 1-AU orbit was considered. This is the closest orbit with which the E-City will be tasked.

Most of the heat generated by the nuclear engines will be directed away from the station in the form of exhaust energy. In addition, the necessity for radiation shielding and use of active thermal control systems will help limit heat input from the engines into the tank. Waste heat generated in the torus section of the station will be controlled by radiators and by re-radiation from the sections facing away from the tank.

Calculations show that with a bare, uninsulated tank, all of the liquid hydrogen would boil off in approximately 1.4 hrs. However, merely by painting the tank white, the boiloff time can be nearly doubled. In order to arrive at a design point, maximum boiloff rate was selected as the sole design criterion. The first step was to determine the surface temperature. Using the assumptions made earlier, the only heat input will be solar radiation. It was then necessary to calculate the maximum heat flux corresponding to the chosen boiloff rate and finally to determine the amount of insulation needed to stay under this limit. The conduction equation was used to solve for the insulation thickness.

Many insulation options are available to the spacecraft designer. As noted earlier, simple external coatings can have a dramatic effect on skin temperatures and will be utilized on the current design. More critical in a cryogenic installation is the insulating material between the outer skin and the inner pressure vessel. Multi-Layer Insulations (MLI) can offer a performance increase of up to 600 times that of plain fiberglass based on thermal conductance. The principal behind the MLIs is that of multiple layers of radiation shields separated by low conductance spacers. The MLI chosen is made of 0.0005" aluminum foil radiation shields with fiberglass mat spacers. This additional mass of the insulation adds approximately 6.4% to the tank mass.

Because of the tremendous amount of heat generated internally by the E-City, some system must be used to actively dissipate this heat. Research done in the phase one report was utilized in the selection of the particular system, and work done in this year emphasized sizing the system.

Several criteria considered when choosing which radiator in use were: external environment, amount of waste heat to be rejected, radiator surface area, circulating fluid system, and micrometeroid damage sensitivity. Ideally the radiator must not depend on surface area while minimizing the mass.

Two types of radiators that were considered for our application were the Liquid Droplet Radiator (LDR) and the Rotating Bubble Membrane Radiator (RBMR). Briefly, the LDR uses nozzles to spray molten metal onto a collector. As the metal droplets travel through space, between the spray nozzle and collector, they radiate their

heat to space. The mass of the LDR is low because the metal droplets are the actual radiator and the majority of the mass is concentrated in the supporting structure. No protective shielding is needed because any meteoroids simply pass right through the spray carrying some of the molten metal with it. The major disadvantage of the LDRs is this loss of metal, which also can occur if the spray nozzles are unable to maintain an accurate aim on the collector.

The system chosen was the RBMR. It uses a two-phase working fluid with an operating principle similar to the LDR. In this system the molten metal is sprayed onto an outer envelope or bubble. The droplets condense and radiate energy as they hit the bubble. By rotating the radiator, the metal droplets are collected in a trough around the circumference by centrifugal force and recirculated again for reuse. The advantages of using this type of radiator are its high hear capacity, relatively low mass, and resistance to critical meteoroid damage. A final consideration is that spray nozzle accuracy would not be a problem since the system is fully enclosed. Since it will be located on the despun portion of the space station, it will need some form of drive to spin it, but this should not entail a great mass penalty.

Once the radiator configuration was decided upon, it was then necessary to arrive at a size and placement for it. A computer program was written to determine the amount of heat generated by the various E-City modes of operation and then to calculate the needed radiating surface area and the dimensions of such a system. The heat sources that were taken into account were the propulsion units and the power generation system. The program requires inputs such as: configuration and operating mode; reactor powers of power plant, propulsion engines, and control thrusters (if used); power conversion efficiencies; power required by the ship; and number of engines or thrusters. The program then calculates the total amount of waste heat that must be dissipated and the necessary radiating surface area. In addition, the output gives the dimensions for three possible geometric configurations corresponding to that surface area. The results are shown in Table 4. These results assume that nuclear thrusters will not be utilized due to their slow startup time and that the engines and reactor operate at full power at all times.

Table 4 Active thermal control system design
parameters for Phase 2 start-up case

Power of main reactor (MWth)	5,000
Power conversion efficiency (%)	40
Power for ship ops (MWe)	22.85
Number of engines	14
Reactor power of start-up engine (MWth)	160,000
Reactor power of each engine (MWth)	160,000
Engine waste heat percentage	0.0
Waste heat from main reactor (MWth)	4,977
Waste heat from start-up engine (MWth)	97,600
Waste heat from main engines (MWth)	0.0
Total waste heat to dissipate (MWth)	102,577
Surface area needed for radiator (sq m)	1,149,301
Length of a cylindrical radiator of radius 100 m (m)	1,1830
Radius of a spherical radiator (m)	311
Major axis of an ellipsoid radiator w/minor axis of 50 m(m)	431

Summary of Results

The summary of the masses of the E-City for the Saturn
envelope mission is given in Table 5.

Table 5 Masses of E-City components
(millions of kgs)

Component	First Guess	Modified Guess	Optimized
Torus	84.9	84.9	185
Shield	1416.3	1416.3	1416.3
Tank	49.1	124.4	58.3
Spoke and shaft	0	2279	2.39
Other	0	0	125.6
Dry mass	1551.9	3909.1	1840.12
Propellant	6503	16380.4	7710.6
Total mass	8054.9	20289.5	9550.7

References

1. "Project WISH: The Emerald City Phase II," The
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2. "Project WISH: The Emerald City Phase III," The
   Ohio State University, NASA/USRA Advanced
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3. "Project WISH: The Emerald City Phase I," The Ohio
   State University, NASA/USRA Advanced Space
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