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Technology Requirements for an Orbiting Fuel Depot—A Necessary Element of a Space Infrastructure

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TECHNOLOGY REQUIREMENTS FOR AN ORBITING FUEL DEPOT--
A NECESSARY ELEMENT OF A SPACE INFRASTRUCTURE

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Abstract

Advanced planning within NASA has identified several bold space exploration initiatives. The successful implementation of these missions will require a supporting space infrastructure which would include a fuel depot, an orbiting facility to store, transfer and process large quantities of cryogenic fluids. In order to adequately plan the technology development programs which will be required to enable the construction and operation of a fuel depot, a multi-disciplinary workshop was convened to assess critical technologies and their state of maturity. Since technology requirements depend strongly on the depot design assumptions, several depot concepts are presented with their effect on criticality ratings. Over 70 depot-related technology areas are addressed.

Introduction

In the past three years in the United States, there has been an increased emphasis on constructing a strategic plan for the nation's civilian space program. In 1985, the National Commission on Space was chartered by the President to develop a vision of the space program well into the next century. Their report[1] urged "exploration and development of the space frontier," including human settlements "from the highlands of the Moon to the plains of Mars." In 1986, the NASA Administrator asked Dr. Sally Ride to lead a study to define potential space initiatives which could make that vision a reality. That study[2] presented four bold initiatives: (1) a piloted mission to Mars, (2) an outpost on the Moon, (3) a robotic exploration of the solar system, and (4) an intensive and extensive study of the planet Earth. Before deciding which, if any, of these initiatives are to be pursued, further study is necessary in order to assess the benefits, feasibility, cost, and the technology development that will be required to that will be required to enable their accomplishment.

There is a growing consensus that an extensive space infrastructure, not currently in place, will be needed to achieve these initiatives, especially the manned missions to Mars and the Moon. An essential element of this infrastructure is a fuel depot, a facility that would perform several functions, including storage and transfer of vast supplies of fluids, most of which could be at cryogenic temperatures. Such a depot would be required because of the enormous quantity of fuel that would be delivered, stored, and transferred on orbit to support these missions. As an example, about one million kg of fuel would be required for the Mars mission.

To understand the technology development which will be required to build an orbiting fuel depot, a study was conducted under the direction of the NASA Office of Aeronautics and Space Technology (OAST). The purpose of the study was to define the functions that a space-based depot would perform, to identify the technologies necessary to perform those functions, and to assess both the mission criticality and the maturity of these technologies. To accomplish these goals, the OAST Cryogenic Depot Workshop, which was attended by technology experts and mission planners from around the U.S., was convened by the NASA Lewis Research Center in September 1987. Because the technology requirements of the entire depot system were under scrutiny, the attendees represented a broad spectrum of disciplinary backgrounds. A considerable amount of information was collected at the workshop and was assembled into a database for reduction and analysis. The information gathered at the workshop, in most cases, represents the results of discussions involving several experts and, therefore, has the enhanced value that such consensus implies. This paper reports on the findings and conclusions of this Depot Workshop and the subsequent analysis of the data it generated.

Definition

What is meant by an on-orbit fuel depot? In its simplest definition, the fuel depot is a facility where propellants or other useful liquids and gases are stored and transferred from and to vehicles and satellites. The location and design of the depot will be determined by mission requirements. The depot could be located on the Space Station Freedom or on a free-flying platform. In its more complex versions, a depot could be a transportation node where space vehicles are constructed, serviced, stored, and fueled, and where fuels are processed from materials brought from the surfaces of Earth and the Moon. In a later section, Depot Concepts, various design concepts will be discussed along with their implications for technology development.

Depot Users

A space-based fuel depot could support a broad range of activities. These include, in ascending order of fluid quantity, satellite fluid resupply operations, upper-stage operations, lunar transportation, and Mars mission support. The first of these, the capability to resupply satellites in orbit, would increase satellite service life by providing cryogenic coolants for scientific instruments and fuel reserves for station-keeping propulsion systems. Whereas some future satellites, such as the Hubble Space Telescope, have been designed to utilize this capability, others, where retrieval and relaunch have not been shown to be effective, do not have resupply capability. Although a number of satellites could benefit from the existence of an on-orbit resupply capability, the amount of fluid involved would be relatively modest; thus, satellite resupply would not, by itself, provide sufficient justification for an orbiting depot.

More compelling justifications for a space-based depot are associated with the fueling requirements of space transportation systems. Space transfer vehicles (STV's) are currently being designed for a wide range of space operations. These are reusable vehicles, fueled by liquid hydrogen and liquid oxygen, which could deliver payloads from the Space Station to other orbits and retrieve satellites for servicing. The ability to refuel STV's in orbit has been shown[3] to be cost effective and would reduce dependence on earth-to-orbit transportation.

The need for a space transportation infrastructure becomes more evident when one considers the development and operation of a lunar base. Base build-up will require scores of trips to the lunar surface[4]. Resupply from the earth will be necessary until the base can be made at least partially self-sustaining. This support will require frequent trips (10 to 20 per year) by large STV's of the 80,000-lb. payload class that will be refueled at a depot in low earth orbit (LEO).

More advanced concepts create scenarios wherein oxygen is mined from the lunar soil and used as a propellant. The Apollo program has shown that the Moon is rich in oxygen (40 percent by weight). Such propellant production would reduce dependence on Earth resupply and allow easier expansion into the solar system.

Of the currently discussed space initiatives, the manned exploration of Mars would be the most dependent on a space transportation infrastructure, in general, and a fuel depot, in particular. The Mars transfer vehicle would be enormous; most estimates of the mass are in the range of one to two million kg, most of which is due to propellants[5,6]. The vehicle would have to be assembled in LEO, and a depot would be used to collect, store, and transfer the fuel before departure. Support of the Mars mission would create a considerable traffic flow at the depot. Depending on the space transportation fleet in place, the number of tanker sorties could vary from as few as 16 heavy lift launch vehicle (200,000-lb. class) flights to as many as 50 shuttle flights.

Depot Technology Workshop

A two-day meeting, the OAST Depot Technology Workshop, was organized and hosted by the Lewis Research Center on September 17-18, 1988, for the purpose of assessing the technology needs for space-based depots. Over 60 technologists representing a broad range of science and engineering disciplines from industry, NASA, academia, and the Department of Defense, met to discuss the functions and services a depot would have to provide to make such a depot a reality in a time-frame consistent with presently proposed mission schedules.

In order to take advantage of this collection of experts, a system was set up to gather efficiently a sizeable amount of useful information in such a way that the data could be presented in a useful format for interpretation and technology program planning. Technology sub-groups were asked to analyze and rate technologies critical to depot development on the provided data collection sheets. Information collected from these data sheets included the technology area needing development; the objective, approach and end product of the development program; the current maturity of the technology; and its criticality to success of a depot development program. An attempt was made to quantify both the technology readiness and the level of criticality by means of a numerical scoring system. The workshop produced 112 of these technology data sheets, a sample of which is shown in Figure 1.

The data reduction process included entering the 112 data sheets into a computerized database, sorting the technology inputs into common technology areas, and expanding data sheet entries into several areas where more than one technology was presented. The technologies were grouped into five general headings: structures and materials, fluid management, depot operations, orbital operations and logistics, and safety. The technology titles in these groups are listed in the first column of figures 3, 4, and 5. In many instances, a number of workshop participants provided data sheets with similar technology needs; these were grouped under a common title. Some of the 71 titles listed represent multiple data entries.

Depot Concepts

Before an assessment can be made of technology needs for a space-based depot, a clear idea must exist of how this facility will perform its functions; in short, a conceptual design. A particular technology which might be vital for one depot configuration might be unimportant if a different configuration were chosen. One difficulty in performing a depot technology assessment has been the lack of unanimity among mission planners regarding the depot's conceptual design. We have addressed this problem--assessing critical technologies for different concepts--by developing a method that concisely defines a depot. Using this depot definition scheme simplifies the task of documenting how the relative importance of technologies varies as a depot concept changes.

We have found that a depot can be defined to a very useful level of detail if six descriptors are specified. The first of these is the depot's class, which characterizes the activities performed at the facility. Three classes of depot are commonly discussed: storage, enhanced service, and production. By enhanced service, we mean the ability to perform a combination of docking, maintenance, repair, and such other vehicle services beyond refueling as construction and configuration modification. A production class depot is one that receives raw materials, such as water, from supply tankers and, at the appropriate time, produces fuel for vehicles. Because fuel processing is so energy intensive, this class of depot would required high-capacity solar or nuclear space power systems.

The second descriptor is the type of fluid stored, or the depot's content. The major discriminator of fluids in this study proved to be temperature; that is, whether or not the fluid was cryogenic. For the most part, the cryogenic fluids are oxygen and hydrogen, whereas non-cryogenic candidates include water products, fuels, such as hydrazine, and oxidizers.

The third depot descriptor, and one which strongly influences technology criticality, is its configuration. The two major configuration groupings are micro g (or zero g) and variable g. Because of the uncertainties and difficulties associated with transferring fluids, especially cryogenic fluids, in the microgravity environment on orbit, depot configurations have been proposed that place the fluids in an acceleration (or artificial gravity) field. There are three ways to produce artificial gravity on a depot: (1) by providing thrust, (2) by spinning the structure, and (3) by using the gravity gradient. This latter method would require separating the tanks from the center of mass of the depot by means of a tether. The separating distance would have to be large enough for the product of the gravity gradient and the distance to produce a gravity environment wherein fluid management would be simplified. The gravity gradient in LEO is approximately $3.7\text{x}10^{-7}$ g/m, where g is 9.8 m/s^2. This means, for example, that to produce a milli g would require locating the tanks 2.7 km from the depot system's center of mass. It is unclear whether the added operational complexity imposed by an artificial gravity configuration would be offset by the lessening of fluid handling difficulties; such issues are the subject of current studies within NASA.

A fourth element in defining a depot concept is its operations mode, which describes how the depot functions are implemented. A depot might be permanently manned, temporarily manned ("man-tended") or fully automated. The operations mode of the depot has severe implications on the relevant technologies requiring development.

There are two more descriptors that complete the depot definition scheme--location and mission. Various space exploration scenarios have postulated fuel depots in low earth orbits, polar orbits, high earth orbits, orbits around the Moon and Mars, and at libration points. Common to all these locations is a microgravity environment; however, their radiation environments and distance from Earth differ markedly. The descriptor, mission, characterizes the activities to be supported by a depot and thereby defines a traffic model from which design requirements can be drawn. For example, in comparison to a piloted Mars mission, a depot supporting a lunar base mission would experience significantly more vehicle arrivals and departures, but store and transfer a smaller amount of fuel.

These six descriptors, class, content, configuration, operations mode, location, and mission, can be thought of as coordinates in a six-dimensional trade space. One selection from each descriptor class defines a depot concept to a level where a technology assessment can be performed. The depot concept definition scheme is portrayed in Figure 2.

Technology Assessment

The depot-related technologies, their criticality ratings, and states of readiness, as assigned by the workshop participants, are assembled in Figures 3, 4, and 5. A numerical system is used to rate both a technology's level of criticality and level of readiness. There are five criticality levels with the following definitions:

Level 1 - The fuel depot cannot be configured without this technology capability.
Level 2 - There is no alternative to this technology for accomplishing the subsystem performance.
Level 3 - An advance in this technology is required for subsystem operation. Reduced performances would compromise other subsystems and impact the functioning capability of the fuel depot.
Level 4 - The degree of technical advance will define the performance of the subsystem. Alternative means would limit the subsystem performance and compromise other subsystem operations.
Level 5 - Alternate means for accomplishment exist and could be incorporated with a modest compromise in weight, performance, and operating complexity.

The measure of a technology's maturity has been designated by an eight level technology readiness system with the following descriptions:

Level 1 - Basic principles observed and reported
Level 2 - Conceptual design formulated
Level 3 - Conceptual design tested analytically or experimentally
Level 4 - Critical function breadboard demonstrated
Level 5 - Component tested in relevant environment
Level 6 - Subscale system model tested in relevant environment
Level 7 - Prototype system model tested in space
Level 8 - Baselined into production design

The charts in Figures 3, 4, and 5 show how the criticality of a technology can vary depending on the class, content, configuration, and operations mode of the depot. Depot locations and missions were not specifically called out in the charts because, for the most part, they were not judged to be technological discriminators.

A few words on how to interpret the charts are in order. A "G" in the second column indicates this technology is generic in the sense that it is not depot-unique and is a technology that supports other space programs. Numbers in the next nine columns represent criticality ratings. A rating in the Core Depot column indicates that this technology is needed for all depot concepts. When another criticality rating is entered on the same technology row, this indicates that the specific characteristic of this column makes this technology more critical. For example, Advanced Assembly Techniques receives a rating of 2 under Core Depot, because this technology will be required for depot construction no matter what concept is selected. However, the criticality of Space Assembly Techniques becomes more severe if the depot's functions include vehicle servicing, and so the rating changes to a 1 in the Service Class column.

When a technology is not associated with a Core Depot, its criticality rating is entered in the columns that are the most relevant. A double dash signifies that the characteristic of that column causes no change to the rating established in the more relevant columns. A blank indicates that the technology of that row has no applicability to that column.

The current state of maturity of a technology is indicated in the last column. A low number indicates that a comparatively long development program would be required to bring that technology to an adequate state of readiness. A rating combination that shows a high criticality, level 1 or 2, coupled with a low readiness level indicates that this technology is a prime candidate for immediate development.

Fluid management in space is the most crucial technology to be addressed in a depot technology development program as can be seen by the abundance of 1's and 2's in the criticality ratings. The topic of management of cryogenic fluids in microgravity was considered in depth at another workshop[7] at the Lewis Research Center in April, 1987.

Study of Figures 3, 4, and 5 reveals other critical technology needs. The Depot Technology Workshop participants with expertise in space operations identified several critical technologies that are currently too immature for depot applications. These include methods and materials for protection against micrometeoroids and man-made space debris, collision avoidance techniques, leak repair methods, advanced space assembly techniques, autonomous rendezvous techniques, control methods for large flexible structures, and a host of technologies associated with safety and quality assurance. The charts repeatedly point out the advances needed in the technologies of artificial intelligence and expert systems. These technology areas are described in greater detail in the Depot Technology Databook[8], which is a compilation of the data collection sheets described in the Depot Technology Workshop section.

OAST, within its Project Pathfinder, has recently initiated a technology development program that addresses the needs identified in this report. The initial phases will expand on the work of this study and will conduct system studies, from the technology development perspective, that analyze the advantages and disadvantages of the various depot concepts described earlier. An important result of the Depot Technology Workshop has been the heightened awareness that the fulfillment of the vision of space exploration requires immediate attention to depot technology development.

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BASIC DATA

Program: On-Orbit Cryogenic Fuel Depot
Technology Area: Microgravity Fluids Modeling
Prepared By: Sanford Davis
Agency/Company: NASA Ames Research Center
Phone: (415) 694-4197
Contact (If Different):
Phone:

OBJECTIVE

To develop more rigorous phenomenological models for microgravity fluid mechanics applications using available supercomputer resources.

APPROACH

The modeling and verification of planned and projected technology programs requires complex anmd sophisticated computer codes. Codes will be developed to model critical flow problems associated with the fuel depot.

END PRODUCT

Validated codes to model microgravity flows will enable flight experiments to be conducted most efficiently with a focus on the most critical data.

TECHNOLOGY READINESS

Estimated Readiness Rating: 2
Comments:

Level 1--Basic principles observed and reported
Level 2--Conceptual design formulated
Level 3--Conceptual design tested
Level 4--Critical function breadboard demonstrated
Level 5--Component tested in relevant environment
Level 6--Subscale system model tested in relevant environment
Level 7--Prototype system model tested in space
Level 8--Baselined into production design

TECHNOLOGY CRITICALITY ASSESSMENT

Estimated Criticality Rating: 3
Comments:

Level 1--The Fuel Depot cannot be configured w/o this technology
Level 2--No alternative for accomplishing subsystem performance
Level 3--Required for subsystem operation, impact other subsystems
Level 4--Alternate means would limit subsystem performance
Level 5--Alternate means exist and could be incorporated

GENERAL COMMENTS

[Schedule Available?, Current Programs?, Concept Applicable?, etc.]

This technology is most critical for developing the technology and expertise needed for long-term space planning and mission selection.

Fig. 1 Example of a technology assessment data sheet.

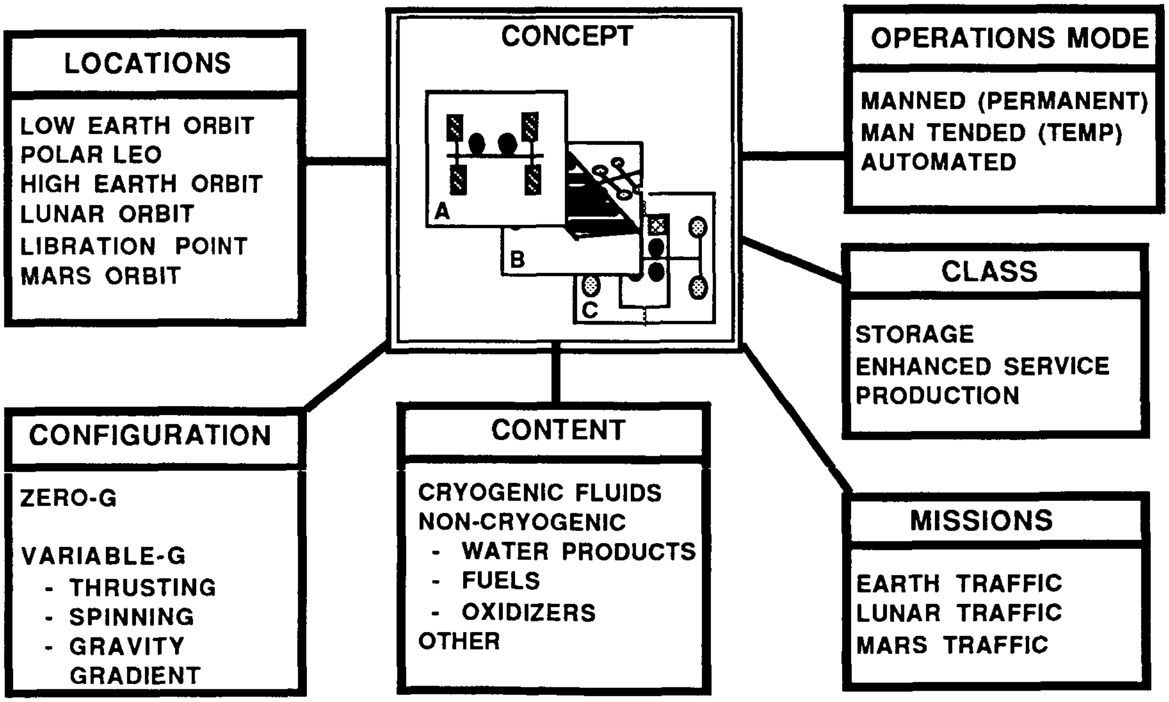

Fig. 2 A depot concept is defined by selecting one descriptor from each of the six classes shown.

TECHNOLOGY	GEN-ERIC?	CORE DEPOT	CLASS		CONTENT		CONFIG		OPERATIONS		TECH READINESS
			SERVE	PROD	FLUID	CRYO	0-G	VAR-G	AUTO	MAN	
STRUCTURE/MATERIALS											
Advanced Insulation			- -	- -		2	- -	- -	- -	- -	2
Leak Before Burst Tankage			- -	- -	2	2	- -	- -	- -	1	2
Long Life Space Materials	G	2	- -	- -	- -	- -	- -	- -	- -	- -	3
Long Life Cryogenic Space Components			- -	- -		1	- -	- -	- -	- -	3
Micrometeroid/Debris Protection	G	1	- -	- -	- -	- -	- -	- -	- -	- -	2
Tank Structural Integrity		2	- -	- -	- -	- -	- -	- -	- -	1	1
Advanced H/O Thruster Materials	G		- -	4	- -	- -	- -	- -	- -	- -	1
Coatings & Sealants	G		- -	- -	2	2	- -	- -	- -	- -	1
Composite Vacuum Jackets			- -	- -		4	- -	- -	- -	- -	3
Low Conductivity Tank Components			- -	- -		3	- -	- -	- -	- -	4
Space Balloon Materials			- -	3		4	- -	- -	- -	- -	1
High Pressure Gas Tanks			- -	3	- -	4	- -	- -	- -	- -	4
Modular/Honeycomb Tankage			- -	- -	5	4	- -	- -	- -	- -	3
Storage Bladders			- -	- -	4		- -	- -	- -	- -	3
ORBITAL OPERATIONS/LOGISTICS											
Advanced Assembly Techniques	G	2	1	- -	- -	- -	- -	- -	- -	- -	3
Advanced EVA Suit	G	3	2	- -	- -	- -	- -	- -	- -	2	4
Advanced Rendezvous Techniques	G	3	- -	- -	- -	- -	- -	2	- -	- -	3
EMU Systems	G	3	2	- -	- -	- -	- -	- -	- -	2	4
Logistics Management	G	3	2	- -	- -	- -	- -	- -	- -	- -	2
Low Cost Propellant Processing	G	4	- -	5	- -	- -	- -	- -	- -	- -	4
Safe Dewar Launch System	G		- -	4	4	3	- -	- -	- -	- -	3
Artificial Intelligence	G	4	1	- -	- -	- -	- -	- -	1	3	3
Automated Traffic Management	G		- -	- -	- -	- -	- -	- -	2	4	2
Automatic Rendezvous Techniques	G		- -	- -	- -	- -	4	3	3	4	3
Expert Systems	G	4	2	- -	- -	- -	- -	- -	2	3	3

Fig. 3 Technology criticality chart in the categories of Structures/Materials and Orbital Operations/Logistics for various depot concepts.

TECHNOLOGY	GEN-ERIC?	CORE DEPOT	CLASS		CONTENT		CONFIG		OPERATIONS		TECH READINESS
			SERVE	PROD	FLUID	CRYO	0-G	VAR-G	AUTO	MAN	
DEPOT OPERATIONS											
Advanced Cryogenic Instrumentation			- -	- -		2	- -	- -	- -	- -	2
Automated Operation/Robotics	G	3	1	2	- -	- -	- -	- -	1	- -	2
Automated Vehicle and P/L Processing	G	3	1	- -	- -	- -	- -	- -	1	- -	2
Large Flexible Structure Control	G		1	- -	- -	- -	2	1	- -	- -	3
Space Power (>500KW)	G		4	1	- -	- -	- -	- -	4	- -	2
Artificial Gravity Generation	G		- -	- -	4	4		1	- -	- -	2
Attitude Control by Momentum Mngmt	G	4	- -	- -	- -	- -	- -	- -	- -	- -	3
Mass Properties Management	G	3	- -	- -	- -	- -	- -	2	- -	- -	1
Oxygen Resistojet (Propulsion)	G		- -	4	- -	- -	- -	- -	- -	- -	3
Supercritical Tanks			- -	- -		4	- -	- -	- -	- -	3
Vibration Control	G	3	- -	- -	2	2	- -	2	- -	2	2
On-Orbit Assembly of Insulation			- -	- -		4	- -	- -	- -	- -	1
On-Orbit Tank Assembly			- -	- -	4	4	- -	- -	- -	- -	1
Water Electrolysis			- -	1	- -	- -	- -	- -	- -	- -	2
Attitude Control by Superconductors		5	- -	- -	- -	- -	- -	- -	- -	- -	1

Fig. 4 Technology criticality chart in the categories of Depot Operations for various depot concepts.

TECHNOLOGY	GEN-	CORE	CLASS		CONTENT		CONFIG		OPERATIONS		TECH
	ERIC?	DEPOT	SERVE	PROD	FLUID	CRYO	0-G	VAR-G	AUTO	MAN	READINESS
FLUIDS MANAGEMENT											
Advanced Coupling System			- -	- -	4	1	- -	- -	1	- -	2
Liquid Supply/Acquisition			- -	- -	- -	- -	1	4	- -	- -	3
Propellant Quality Monitoring			- -	1	- -	- -	- -	- -	- -	- -	1
Slosh Control			- -	- -	- -	- -	1	3	- -	- -	2
Thermal Monitoring/Determination			- -	- -		1	- -	- -	- -	- -	3
Zero-G Liquid Transfer			- -	- -	- -	- -	1	4	- -	- -	2
Hazardous Fluids Management			- -	- -	2	2	- -	- -	- -	2	2
Pressure Control			- -	- -		3	- -	- -	- -	2	2
Advanced Refrigeration			- -	1		4	- -	- -	- -	- -	3
Cryogenics Flowmeters			- -	- -		3	- -	- -	- -	- -	4
Low-G Heat Transfer			- -	- -		- -	3	4	- -	- -	4
Microgravity Fluids Modeling			- -	- -	- -	- -	3	5	- -	- -	2
Zero G. Mass Gaging			- -	- -	- -	- -	3	5	- -	- -	2
Advanced Low G Compressor			- -	2	- -	- -	4		- -	- -	3
Thermal Protection System			- -	- -		4	- -	- -	- -	- -	4
SAFETY											
Leak Repair			- -	- -	2	2	- -	- -	- -	1	2
On-Orbit Safety Specifications	G	2	- -	- -	- -	- -	- -	- -	- -	1	2
Collision Avoidance Techniques	G	2	- -	- -	- -	- -	- -	- -	- -	1	1
Health Monitoring	G	2	- -	- -	- -	- -	- -	- -	- -	- -	2
Leak Detection	G		- -	- -	2	2	- -	- -	- -	1	2
Survivability/Hardness			- -	- -	- -	- -	- -	- -	- -	4	2
Debris Removal	G	3	- -	- -	- -	- -	- -	- -	- -	- -	1
Emergency Jettison/Evacuation Ops			3	- -	- -	- -	3	- -	- -	2	3
Nondestructive Inspection Sensors	G	3	- -	- -	- -	- -	- -	- -	- -	- -	1

Fig. 5 Technology criticality chart in the categories of Fluids Management and Safety for various depot concepts.

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