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Technology Issues Associated With Fueling the National Aerospace Plane With Slush Hydrogen

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TECHNOLOGY ISSUES ASSOCIATED WITH FUELING THE NATIONAL AEROSPACE PLANE WITH SLUSH HYDROGEN

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ABSTRACT

The National Aerospace Plane is a horizontal take off and landing, single stage-to-orbit vehicle using hydrogen as the fuel. The first flights are planned for the mid 1990's. The success of this important national program requires advancements in virtually every discipline associated with both airbreathing and space flight. The high heating value, cooling capacity, and combustion properties make hydrogen the fuel of choice, but the low density results in a large vehicle. Both the fuel cooling capacity and density are increased with the use of slush hydrogen and result in significant reductions in size of the vehicle. A national program to advance this technology and to find engineering solutions to the many design issues is now underway. The program uses the expertise of the cryogenics production and services industry, the instrumentation industry, universities, and government. This program will be discussed to highlight the major issues and display the progress to date.

INTRODUCTION

There are several compelling reasons to build and test the National Aerospace Plane (NASP) X-30 research aircraft. A horizontal take off and landing space launch vehicle would have greatly reduced launch operations cost. A single stage-to-orbit is the most economic alternative for full reusability by minimizing the navigational and propulsion systems for return to the launch site systems and by eliminating the stage integration process. And, hypersonic cruise has many applications in civil transportation and military activity. The X-30 is, therefore, a test bed for demonstrating the advanced technologies that are required for the next generation of flight.

The key enabling technology for hypersonic cruise and single stage-to-orbit are air breathing propulsion systems for the entire flight regime of zero to Mach 25. But, even with these propulsion systems, the vehicle would be too large and too heavy using today's materials and fuels. Hydrogen is the fuel of choice, but its low density produces a large vehicle. The NASP program is addressing these enabling technology areas with strong programs in propulsion, materials, and in the use of slush hydrogen.

The NASP X-30 requires a high energy propellant and active cooling. Hydrogen is the fuel of choice because of its high energy content and because of its cooling capability. Slush hydrogen is 16 percent more dense and, due to the addition of the heat of fusion, has 18 percent more cooling capability than liquid hydrogen. This increased cooling capability is especially important for the NASP because during some portions of the flight the cooling requirements exceed the propulsion requirement for hydrogen. The net effect on the NASP of using slush rather than liquid hydrogen is to reduce the gross lift off weight of the vehicle by up to 30 percent. Most costing algorithms relate cost to weight and, therefore, the use of slush hydrogen on the NASP represents an important new technology. Slush hydrogen has been investigated by several researchers including the National Bureau of Standards. The advantages of using slush hydrogen in space vehicles was recognized and was considered for the Space Shuttle in the early 1970's. Because the technology did not exist beyond the laboratory level it was not selected. The current NASP program is committed to advancing slush hydrogen technologies and demonstrating them on the X-30.

The current slush hydrogen program includes, to varying degrees, vehicle slush system design, flow component modeling, large scale production, ground storage and vehicle servicing, instrumentation, and safety criteria. Models are being developed/modified and predicted results will be compared with experimental results. The objective is to advance the fundamental understanding and to generate design information.

NASP OPERATION/ISSUES

Production

Methods. Slush hydrogen has been produced in laboratories by several researchers. The National Bureau of Standards has reported observations about slush hydrogen produced in small glass dewars using two different production methods. Other researchers have proposed, and in some cases demonstrated, other methods. The methods can be categorized as evaporation and refrigeration. The evaporation method most often used is referred to as the freeze-thaw method. In this method the tank pressure is lowered to the triple point and solid hydrogen forms on the surface. The pressure is allowed to increase, heat leak through the walls melts the solid near the wall, and the solid sinks into the liquid. As this process is repeated the solid fraction is increased up to about 30 percent before the solid cannot be fully covered by the liquid. If the slush is maintained, the configuration (not the size) of the solid crystals changes with time. This process is called aging. With time (aging) the solids pack more densely and more freeze-thaw cycles can increase the solid fraction to nearly 50 percent before the solid cannot be covered by the liquid. The freeze-thaw method is well understood but has not been developed at large scale. The disadvantages of the freeze-thaw method is that it has been a batch process to date. Also, 16 to 20 percent of the liquid hydrogen is evaporated in the process and is either lost or requires additional equipment to reliquefy. Another evaporation method for making slush is to spray liquid into a near vacuum (less than the triple point pressure) to form solid crystals. This method requires fluidizing with liquid to make slush and has not been characterized. Both of these evaporation methods have the additional disadvantage of requiring subatmospheric equipment which introduces the possibility of leaking oxygen into the system and creating an explosive mixture.

Slush hydrogen has also been produced by refrigeration methods. The most tested method is to flow liquid through a tube whose wall is cooled with either cold gas or liquid helium. The solid crystals that form on the surface are scraped off by an auger. The advantages of the auger method are that it is a continuous process (without aging) and that the equipment can be operated above atmospheric pressure. The disadvantages are that the method is not well characterized and, more importantly, requires an expensive refrigerant. A magnetic refrigerator has also been proposed but has not been characterized except at small scale.

The production of slush hydrogen is seen as an engineering problem that is manageable. The most energy efficient method has not been determined nor have trade studies been completed comparing the capital cost to the operating costs. Because of transfer and storage considerations to be discussed later, it seems apparent the slush should be produced at the vehicle loading site. Therefore, the logistics of supplying the site will be the same as with liquid hydrogen. Certainly the production of slush hydrogen will be more expensive than just liquid and the capital equipment will be rather expensive, but the payoff for the NASP and for many other space vehicles makes this an important technology for our nation to develop.

Issues. The issues associated with the production of slush hydrogen are primarily engineering problems. There are some very significant technologies that are required. In subatmospheric systems where the contamination of the hydrogen with oxygen is a possibility, methods for detecting the presence of oxygen and experiments to determine acceptable amounts of oxygen must be developed. The aging process that is required to get the solid fraction up above 50 percent adds a significant time to the production which increases the storage requirements and/or lengthens the turn around time between flights. Methods to speed this aging process must be found. These and other issues are shown in Table I.

Ground Operations

Requirements. The requirements for the ground operations segment to support the NASP are functionally the same as for any research aircraft, but with added emphasis on developing the technology for rapid turnaround. The use of a cryogenic propellant in a research airplane is also new, but there is considerable experience with rockets. The quantity/distance safety requirements are assumed to be the same, but more study is required. The use of slush hydrogen does add several new problems not treated in the use of liquid hydrogen in space vehicles. The low latent heat of fusion means that low heat leak into the system will cause the solid hydrogen to melt. The result is that the storage and transfer systems must be designed to have much lower heat leak than is required for liquid hydrogen systems. Starting with equal amounts of liquid and 50 percent slush hydrogen in similar systems the amount of heat which would completely melt all of the solid in the slush would only vaporize 6.5 percent of the liquid hydrogen. The slush systems require similar insulation and handling technology as liquid helium systems. Because low heat leaks into the slush will cause changes in the density of the fluid, the slush systems are susceptible to acoustic instabilities. These instabilities may occur in the main flow lines and also in the instrumentation lines.

In the process of loading liquid hydrogen into a spacecraft it is necessary to top off the liquid as heat addition causes boiloff and the venting of gaseous hydrogen. The process of loading and holding a slush hydrogen tank is different because heat addition melts solid, lowers the density and causes liquid to be vented. The process of loading and holding a tank with 50 percent solid will require considerably more turnover of product to upgrade the slush in the tank. Studies must be conducted but it seems apparent that the degraded slush must be recirculated and reprocessed. The thermal dynamics must be modeled and the equipment to accomplish this upgrading process must be developed.

To keep the weight of the NASP as low as possible, the flight insulation system will not be as low in heat leak as the storage system. Therefore, the long ground holds that are likely to be required for such a complicated research aircraft will be a problem, especially after roll out from the servicing facility. A portable upgrade system may be required to solve this problem.

Even though many precautions are taken, debris is present in the liquid hydrogen. In loading space vehicles, the liquid hydrogen is filtered both as it is introduced into the vehicle and again just before the engines. With slush hydrogen conventional filtering methods cannot be used. Several alternatives have been considered. The entire storage and transfer system could be maintained at extreme levels of cleanliness and the fuel filtered as a liquid before it is made into slush. Another method would be to design the engine pumps such that they could tolerate larger debris. Since the slush will be melted in the pumps, filters could then be placed downstream of the pumps and ahead of the propulsion equipment.

The method of transferring slush hydrogen from the storage tanks to the vehicle must be studied further but initial studies indicate that pumped transfer is preferred because there will be less heat addition to the fluid from the pumping than there will be to the storage tank from a warm pressurant. The National

Bureau of Standards has pumped slush hydrogen with no apparent problems but much more information is needed. Another transfer issue is maintaining a critical velocity to carry the solids along with minimal friction heating of the fluid. This critical velocity has been determined for small lines but scaling and design rules must still be determined. Pressure drop across orifices and venturis has been observed to be virtually the same as with triple point liquid.

Issues. The major issues in storage and ground operations are the lack of design criteria and the lack of models for the fluid dynamic and thermal dynamic processes. The filtering and the fluid transfer methods will also require considerable technology development. Other issues are shown in Table II.

Flight Operations

Requirements. Because slush hydrogen is in equilibrium with vapor-solid-liquid only at the triple point of 13.8 K and 52.8 mm Hg (1.02 psia) the pressurization of the flight tank to provide net positive suction pressure for pumps or to cause outflow presents a difficult problem. If gaseous hydrogen is provided as pressurant, cooling at the ullage-slush interface would cause the pressurant to be condensed and result in a drop in the tank pressure. This process fails to produce the desired pressure or worse, can cause the tank to collapse structurally if it is not designed to accommodate such loads. If temperature stratification could be maintained such that the slush-ullage interface is slightly above the triple point temperature, ullage condensation could be prevented. Vehicle motion, and the perceived need to continually stir the slush, complicate this approach. An alternative is to pressurize with a noncondensable like helium. The problem with this approach is the added weight of the helium systems and the inert gas itself. Much more work must be done to determine the best way to pressurize slush hydrogen tanks. This is especially true for vehicle tanks where there is such a premium on low weight and low volume.

In the NASP mission profile there are times when the cooling requirements for hydrogen exceed the propulsion requirements. If, during these times, the extra hydrogen is routed through the propulsion system, the performance of the system is degraded even though additional thrust is produced. An alternative is to route the extra hydrogen back to the vehicle slush tank. Although the addition of this thermal energy to the vehicle tank would degrade the cooling capability of the fluid, it would be adequate at other times in the mission profile when the cooling requirements were less demanding. This process is called recirculation. The technology issues associated with introducing warmed fluid into the slush tank, with net outflow while maintaining pressure will require considerable experimental work and some sophisticated models.

Vehicles are usually tanked such that the propellant mass at lift-off is known to an accuracy of 1/2 percent. To achieve this kind of accuracy with the slush hydrogen, two phase quantity gauges will be required. Several techniques have been demonstrated in the laboratory but selecting the best type to be used in the NASP vehicle tank, which will have many internal obstructions, will be a significant challenge. Density gauging methods that have been demonstrated in the laboratory use radiation attenuation and changes in the dielectric constant as indications of the density. There has been significant progress but demonstrations in large tanks with internal obstructions are required. Two-phase mass flow meters will be required, at least on the research flights where redundant engine performance measurements will be desirable. The most promising types are Coriolis effect meters and constant power thermal meters. Other desirable flight instrumentation would be liquid level sensors and fiber optic means for making direct observations into the tank.

The hydrogen must be pumped to high pressure to be used as a coolant and as the propellant. The energy added to the fluid in the pumping process will melt the solids and, therefore, the hydrogen downstream of the pump will be at a lower temperature than if liquid hydrogen would have been introduced at the pump inlet. The National Bureau of Standards has pumped slush hydrogen with no observable damage to the pump but the head rise was small and there are only limited data. More work is required to fully establish this technology. An alternative is to screen the outflow from the vehicle tank such that only triple point liquid enters the pumps. In this scenario the solids would be melted by the addition of heat to the tank through the insulation or from the pressurant.

Issues. Pressurization is the most significant single issue. Trades must be made for risk, weight and volume using both hydrogen and helium or combinations of the two as pressurant. Recirculation is the next most significant issue. Models for the thermal dynamics, stratification, tank motion and heat transfer must be developed for slush hydrogen and then these models must be verified with experiments. Several new instruments are also required including density gauges to determine the quantity of slush in the tank, flow rate meters for performance measurements, liquid level sensors and fiber optic methods of observing the slush in the tank. The technology for pumping slush hydrogen without damage to the pump and with predictable knowledge of the thermal condition of the fluid must be demonstrated. The flight operations issues are shown in Table III.

SLUSH HYDROGEN RESEARCH PROGRAMS

In addition to the contract specific work that the major airframe and propulsion contractors are doing to advance the technologies for the National Aerospace Plane, there is a large government-sponsored program to mature those technologies which are of a more generic nature. This group of tasks is called the Technology Maturation Program (TMP). The development of slush hydrogen technology is one of the major TMP tasks. The National Aeronautics and Space Administration (NASA) Lewis Research Center has the lead role for the slush hydrogen TMP task. Several organizations are currently contributing to this effort. The National Bureau of Standards in Boulder, Colorado is working on instrumentation and physical properties. There is a contract with the McDonnell Douglas Corporation and their subcontractors, Wyle Laboratories, Martin Marietta Denver Aerospace and Air Products and Chemicals, Inc. to do large scale experimental work in production, pressurization, transfer, and modeling. NASA Lewis is also doing large scale experiments in production, storage, pressurization, transfer, slosh and instrumentation all with particular emphasis on varying many parameters and verifying models. The University of Michigan is working on the gellation of both hydrogen and slush hydrogen and the University of California Los Alamos National Laboratory is leading the safety tasks.

The tasks being worked by this slush hydrogen team are discussed below.

Vehicle Slush System Design

The NASP airframe contractors are currently investigating concepts for the slush hydrogen systems and will be making selections and beginning preliminary designs during 1989. There is a dire need for design criteria and for verified models. Figure 1 shows the vehicle system design data and activities that are planned. In 1989 the physical properties of slush and gels will be defined experimentally and there will be a thorough assessment of instrumentation. Pressurization will be demonstrated with both hydrogen and helium, critical flow velocities determined and several system applications simulated primarily using existing hardware. In 1990-91 the emphasis will be on scale changes, broader ranges of critical parameters and the simulation of critical vehicle operations. These data will be used to verify models. The 1992-93 time frame will be focused on the demonstration of procedures using large scale hardware of the contractors design and/or concept.

Flow Component Modeling

Flow component modeling activities and planned outputs are shown in Fig. 2. Many of the necessary models are in place and have been used successfully for triple point and for subcooled hydrogen. Some modifications are being made to properly model slush. These include condensation, adding the option of considering three phases and stratification in the ullage. Thermal dynamic and heat transfer models are being developed/ modified for both tanks and lines. Slush models are also being modified. These models will be verified using the data from the various laboratory scale and large scale experiments.

Large Scale Production

The large scale production activities are shown in Fig. 3. Because of the funding constraints in the program, the production activities are limited. Two different size augers are being tested. The major test facilities are being supported by freeze-thaw production systems but the emphasis is not on studying this production method. Safety issues are being studied and there is a contract effort to conduct trade studies on production methods.

Ground Storage and Vehicle Servicing

The ground storage and vehicle servicing technologies are being addressed by the slush hydrogen team as shown in Fig. 4. Other more design specific issues are being addressed by the individual airframe contractors. Tanking, topping and upgrading tests and the definition of procedures and the correlation of models will be the primary focus. Trade studies of various ground operations scenarios as functions of cost, turnaround time and risk will be conducted. In 1990-91 ground hold and insulation schemes will be tested and the results will be correlated with the models.

Instrumentation

The instrumentation tasks planned are shown in Fig. 5. A survey of available instruments and of various laboratory methods to measure density, and flow rate with slush hydrogen was completed in 1988. Several different density meters will be tested in 1989-90 to determine the operating characteristics and applicability to the obstructed interior of the NASP vehicle tank. Line density meters, flow meters and liquid level sensors are also being tested and evaluated. Calibrations of these instruments will be completed in the 1989-91 period.

Safety Criteria

The safety criteria for slush hydrogen will be based on the extensive set of criteria that exists for liquid hydrogen. The planned activities are shown in Fig. 6. Studies will be conducted to determine what different procedures might be required with slush. It is anticipated that some experimental work will also be required to establish additional criteria. One of these may be to determine the explosive limits of frozen oxygen in slush hydrogen.

CONCLUDING REMARKS

The challenge of flying an airplane using liquid hydrogen as the fuel, including take off and landing operations, has not been done. The National Aerospace Plane will use slush hydrogen. The challenge is great but the benefit to both the NASP and to other space vehicles makes this both an interesting and necessary technology for our nation to acquire. No real roadblocks have been identified to date by the national team working on the problem. There are many engineering problems but they all seem to have solutions that do not require major technical breakthroughs. If these engineering problems can be solved in the next few years slush hydrogen will be the fuel of choice for the National Aerospace Plane and for many other applications into the next century.

TABLE I. - SLUSH HYDROGEN PRODUCTION ISSUES

- Selection of slush production method
  - Energy efficiency
  - Capital investment
  - Safety
- Accelerating the aging process
- Oxygen contamination limits/detection

TABLE II. - SLUSH HYDROGEN GROUND OPERATIONS ISSUES

- Ground hold
  - With flight weight insulation
  - Need for umbilicals
- Transfer method
- Upgrading
- Acoustic instability
- Critical velocity
- Design criteria/models
- Filtering
- Safety procedures

TABLE III. - SLUSH HYDROGEN FLIGHT OPERATIONS ISSUES

- Pressurization methods/models
- Recirculation
- Thermal dynamic/heat transfer models
- Instrumentation
  - Quantity (density) gauge
  - Flow meter
  - liquid level sensor
- Pumps
- Screens

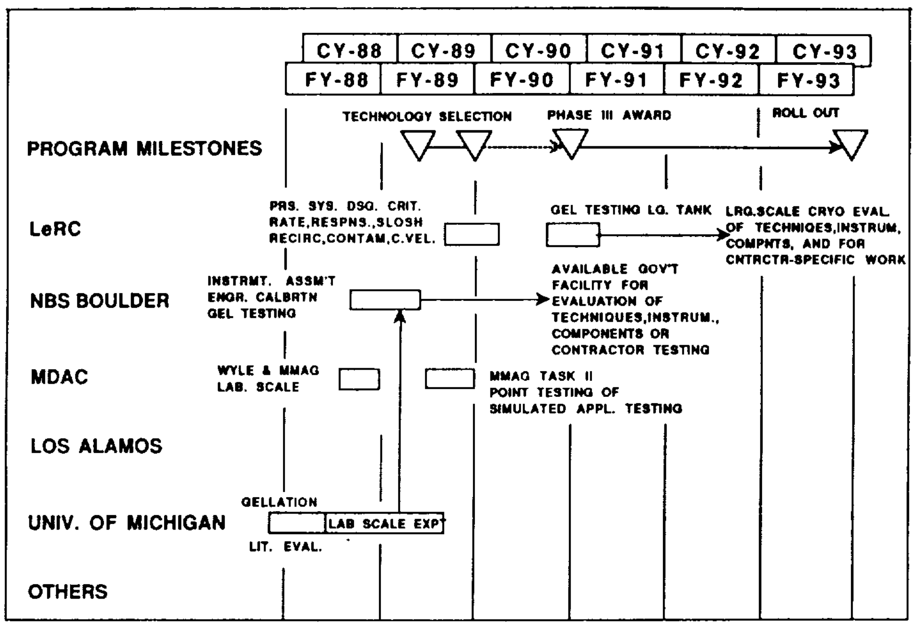

Figure 1. Programs in Vehicle Slush System Design

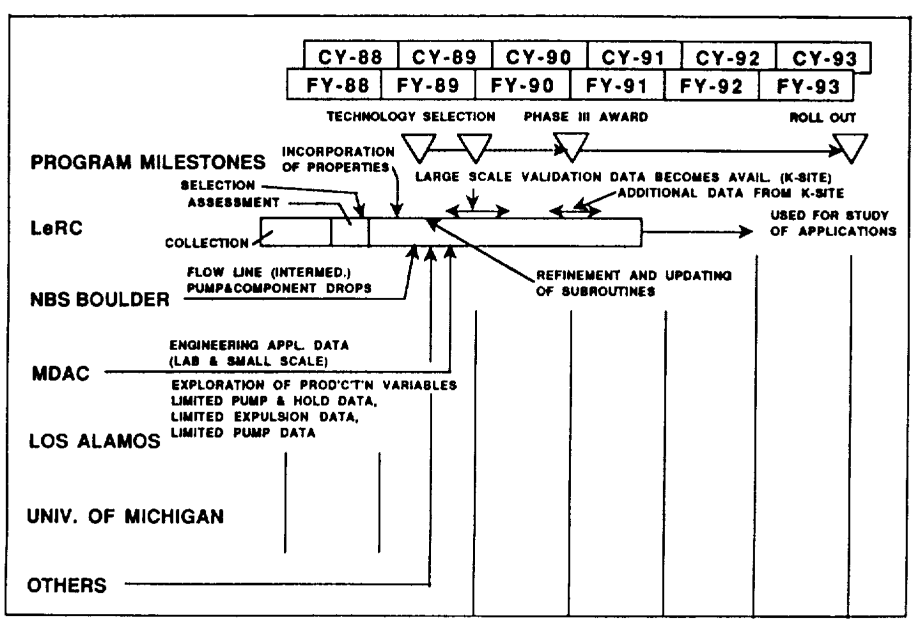

Figure 2. Programs in Flow Component Modeling

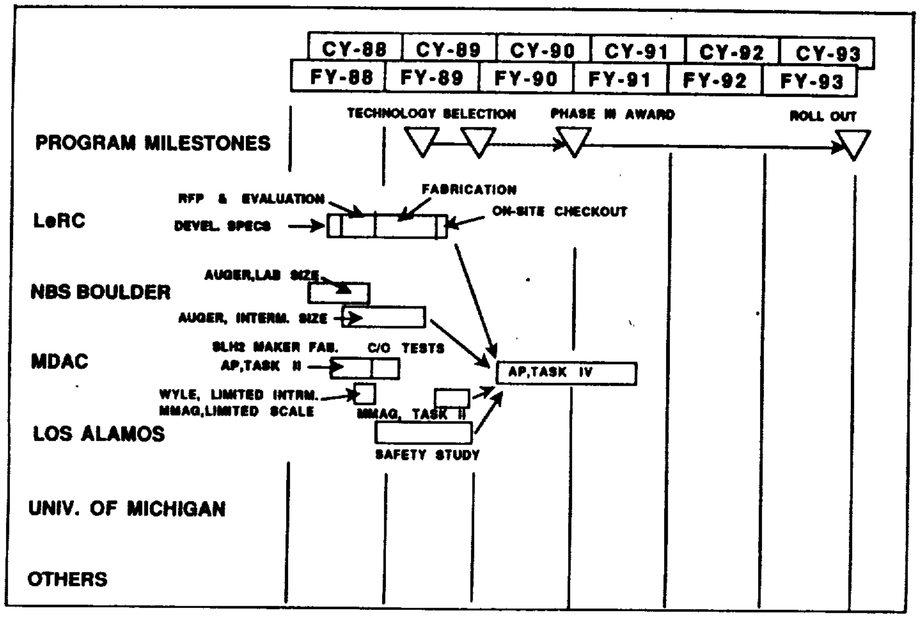

Figure 3. Programs in Large Scale Production

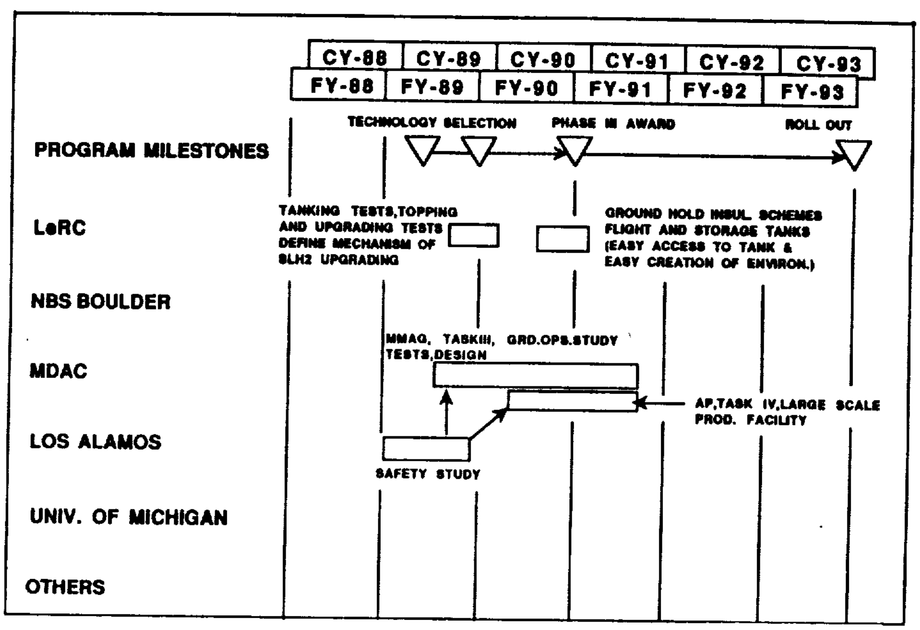

Figure 4. Programs in Ground Storage and Vehicle Servicing

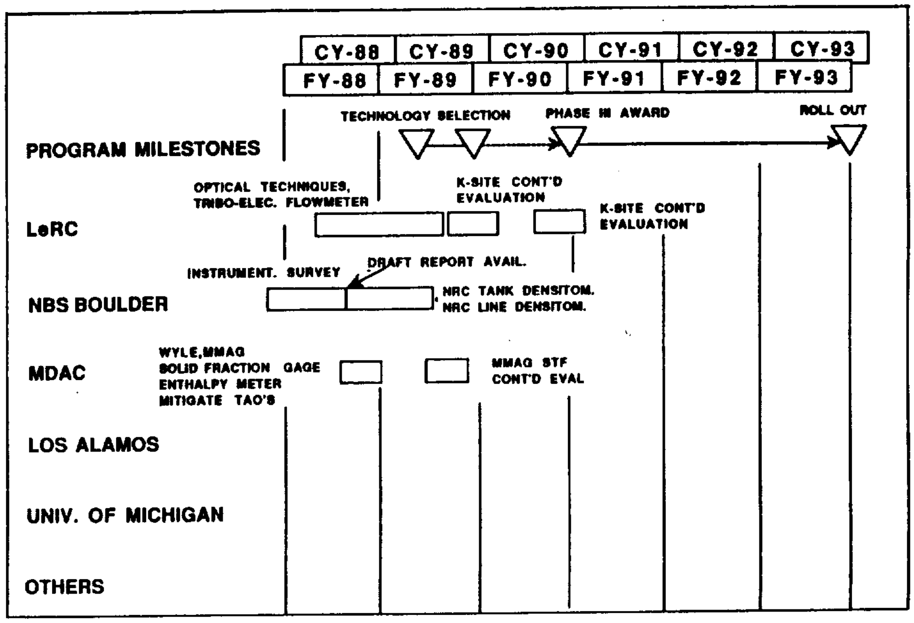

Figure 5. Programs in Instrumentation

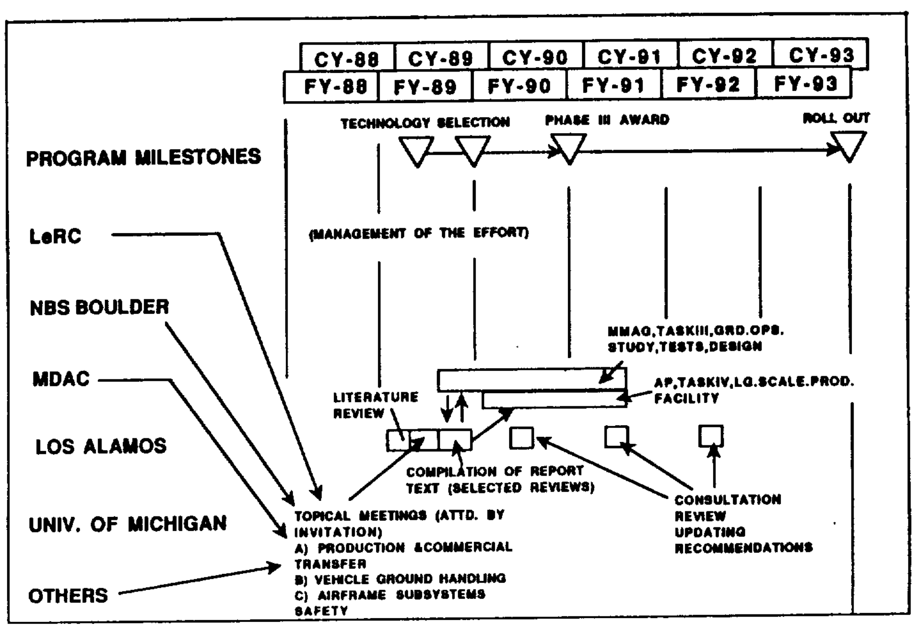

Figure 6. Programs in Safety Criteria

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