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# OBIGGS For Fighter Aircraft

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## ABSTRACT

Advanced technology air separation modules for use in on-board inert gas generation systems (OBIGGS) were investigated in a recently completed Air Force development program. These modules use hollow fiber permeable membranes that are compatible with a fighter aircraft environment and have no moving parts. Extensive ground testing revealed that the advanced modules offer an order of magnitude savings of weight and volume compared to other air separation modules. Hence, the advanced modules were used in an in-depth study of OBIGGS for fighter aircraft applications. A best choice OBIGGS for a generic ATF configuration and a comparison of the best choice OBIGGS with other aircraft fuel tank fire protection systems are discussed.

PREVENTING FUEL TANK FIRES and explosions by inerting airplane fuel tanks with nitrogen is a technique which is receiving much attention throughout the DoD community. Fuel tank inerting with nitrogen functions by reducing the oxygen concentration level in the fuel tank vapor space (ullage) to a level that will not support combustion. Based on extensive experimental evidence, an oxygen concentration of less than 9% has become the accepted criterion for nitrogen inerting to ensure against fuel tank fires and explosions. This criterion will provide explosion protection against combat threats at least through the 23mm HEI threat.

Liquid nitrogen ($LN_2$) fuel tank inerting systems are currently being used on the Air Force C-5 fleet. While an $LN_2$ system provides the desired level of protection, its use entails significant logistics problems. The $LN_2$ must be replenished frequently, affecting turn-around time and sortie rate. One of the proposed solutions is to replace the $LN_2$ system with an On-Board Inert Gas Generation System (OBIGGS). During flight, the OBIGGS physically reduces the oxygen content of the high pressure engine bleed air to less than 9% by volume (typically 5%). The OBIGGS does this by separating high pressure air into two streams: an inert product gas and a waste gas. The product gas, termed nitrogen enriched air (NEA), is supplied to the fuel tanks, whereas the oxygen rich waste gas is normally expelled overboard.

The part of the OBIGGS which does the separation is termed the Air Separation Module (ASM) and is the heart of an OBIGGS. Two different ASM technologies are available: Molecular Sieve (MS) and Permeable Membrane (PM). The MS based ASM is currently used in the AAH-64 and is planned for the C-17 and V-22. However, the recent performance improvements in PM technology make it far superior and this advanced PM performance is the basis for this paper.

Two different concepts exist for an OBIGGS designer: the stored gas concept and the demand concept. The demand OBIGGS is designed with a large ASM capable of meeting the highest flow requirements, usually during descent. Therefore, the size of a demand OBIGGS is based on maximum inert gas flow rate. The stored gas OBIGGS, on the other hand, uses a high pressure compressor and storage bottle to accumulate a sufficient quantity of NEA to satisfy short term, high flow rate requirements while generating NEA at a steady rate but much lower than the maximum rate of a demand OBIGGS. The size of a stored gas OBIGGS is based on the average inert gas production rate and the total mass of stored NEA required.

The Air Force Aero Propulsion Laboratory has sponsored a contract with the Boeing Military Airplane Company to investigate the application of OBIGGS technology to a fighter. Specifically, the objective of the contract was to define an optimum OBIGGS for an "ATF like" airplane and compare it to other available explosion protection techniques. Detailed

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information on this effort is available in the final report (1).

## FIGHTER REQUIREMENTS

**FUEL SYSTEM** - The generic ATF aircraft chosen for this study features a one man crew, twin engines with empty/gross weights of 32,099/58,007 pounds. The fuel system has three body and two wing fuel tanks with a total volume of 409.8 cubic feet (3066 gallons) or about 19,345 pounds of JP-4. The fuel system is similar to the F-15, featuring:

- Refuel valves in each tank (5 total)
- Separate vent line from each tank to a vent box
- Vent box in each wing
- Separate transfer lines and refueling lines
- Single point refueling and defueling
- Aerial refueling system compatible with KC-135 and KC-10 tankers

The F-15 fuel system was modeled using the following assumptions:

- All tanks were modeled as one large tank
- Fuel management is not a factor for consideration
- Ullage oxygen concentrations were uniform throughout all the tanks at any given time

The pressurization schedule and dive valve setting were the same as the F-16 normal mode:

- Climb valve setting = +6.4 psig
- Demand regulator setting = +4.7 psig
- Dive valve setting = -0.75 psig

**GROUND RULES FOR MISSION SELECTION AND TRADE STUDIES** - During mission selection and trade studies, the following ground rules applied:

- Full time inerting for the design mission, including emergency or unplanned descent was the goal. Short periods of uninert time over friendly territory were considered in weight trade studies.
- The stored gas OBIGGS concept was the baseline
- The OBIGGS produced NEA5 (NEA with 5% oxygen)
- The fuel was JP-4

**MISSION SELECTION** - The major sizing criterion for a stored gas OBIGGS was the total weight of NEA required to inert the mission, while the major sizing criterion for a demand OBIGGS was the maximum rate of tank repressurization. Several missions were analyzed to determine the total NEA weight and storage requirements for the stored gas design mission (worst case) selection. The missions selected for analysis were high and low altitude air to ground, subsonic weapon delivery training and two air to air combat scenarios. These missions had a significant number of altitude excursions, thereby increasing the repressurization requirements. The design mission selected was the air to air combat intercept scenario shown in Figure 1.

The design criterion for a demand OBIGGS was the maximum descent rate. For this study, the maximum descent rate was based on the structural limit of the aircraft during descent. This hypothetical descent required only 54 seconds and included an initial flight point of Mach 2.2 at 70,000 feet, a vertical attitude at 60,000 feet and a max G pull-out from 10,000 feet to sea level at Mach 1.2. Note that this descent profile, requiring high repressurization flows, will only affect the NEA delivery hardware (line sizing) for a stored gas OBIGGS. Conversely, the large repressurization rate requirements were fundamental to sizing a demand OBIGGS.

## AIR SEPARATION MODULE PERFORMANCE

The application of OBIGGS to fighters is generally the most demanding of all aircraft types due to the relatively small size and rapid descent rates of a fighter. The latest developments (Figure 2) in permeable membrane based air separation technology now make even fighter applications practical. Surveys of this technology indicate that more than a dozen independent companies are conducting aggressive membrane R&D programs. At least one company has demonstrated an order of magnitude improvement in performance based on size and weight.

Under the sponsorship of the Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base, two of the most advanced permeable membrane based ASMs were subjected to extensive testing over a one year period. The objective of these tests was to verify the rather extraordinary performance gains claimed by the membrane manufacturers using independent experiments and evaluate their suitability for aircraft environments.

Tests were conducted in the following areas:

- Performance Mapping ($\%O_2$ and Recovery vs Inlet Pressure, Altitude, Temperature and NEA Flowrate)
- 2000 Hours of Endurance Testing
- Inlet Moisture Sensitivity (up to 180 grains)
- Hot/Cold Start-ups ($-60^{\circ}F/+140^{\circ}F$)
- 1000 On/Off Cycles
- Operational Vibration Sensitivity Tests (MIL-STD-810D)
- Inlet Air Contamination Sensitivity

(Recovery is the ratio of inert gas production rate to supply air flow rate).

The performance mapping results indicated that performance actually exceeded the initial claims of a factor of 10 improvement. ASMs from A/G Technology and Permea were tested. A comparison of ASM weights for these two units and existing technology is shown in Figure 3. Each ASM in Figure 3 was evaluated at its design operating temperature. Obviously, those systems capable of operating at higher temperatures are desirable although any operating temperature below the bleed air temperature will require some bleed air cooling. Note that the A/G Technology ASM offers the potential for greatly reducing the weight of an OBIGGS. The A/G Technology Advanced ASM performance data was used in this fighter application study.

Over the entire gamut of tests listed above, no aircraft environmental problems were identified (such as vibration or extreme cold starts) except a minor performance degradation due to inlet air contamination. The productivity of the A/G Technology ASM was found to degrade at the rate of approximately 1% per 100 hours while operating on inlet air contaminated with 9 PPM (Parts Per Million) of thermally degraded synthetic oil vapor. (All particulate and aerosol contamination was removed by high quality inlet air filtration during all tests.) When the vapor contamination level was reduced below 3 PPM, the rate of performance degradation was also reduced to essentially zero (less than 2% per 1000 hours).

The need for high quality particulate and aerosol filtration on the inlet air to any ASM, regardless of separation principle, is mandatory. However, as the performance of advanced membrane systems increases, the flowrate of air per unit area of membrane also increases and results in an increased sensitivity to contaminants. ASM's tested in this program had a membrane area ten times smaller than previous ASM's. As the membrane area is further reduced, contamination is expected to be an increasingly difficult problem. Note that contamination would be significantly less of a problem in a demand system which would operate near its maximum flow capacity only for short periods of time.

## PRELIMINARY DESIGN

**BASELINE STORED GAS OBIGGS** - The baseline stored gas OBIGGS was sized to inert the OBIGGS design mission, previously discussed, where the NEA generation rate is .67 pounds/minute and the NEA storage requirement is 41 pounds. The major components for OBIGGS sizing were:

- o Advanced permeable membrane air separation module
- o Pre-cooler (ram air cooling)
- o Chiller
- o Storage bottle(s)
- o High pressure compressor (electric)
- o Boost compressor (ASM inlet pressure >=60 psig)

**TRADE OFFS** - The changes in the weight of the major components of the baseline stored gas OBIGGS were determined for comparison and effect. Areas for consideration included operational and environmental factors and weight reduction schemes. Survivability and vulnerability were also considered in these comparisons. Many additional trade studies were conducted and these are documented in the final report (1).

One trade was to allow the maximum ullage oxygen concentration to increase to 12% as the result of the dive valve opening in an unplanned or final descent. This did result in weight savings for a stored gas OBIGGS from 21 to 52 pounds, but the significantly higher survivability/vulnerability risk of admitting air to the ullage and vent system negated the potential weight savings. A part-time inerting system which provided inerting for combat only, was 31 pounds lighter. However, this weight savings did not off set the decrease in protection offered (51% of the mission protected compared to 84% for the baseline system). The effect of partial fuel loading to enable the aircraft to carry a larger payload for a shorter mission resulted in a 35 pound weight increase. Since normal deployment of the ATF included completely full tanks, partial fuel loading was considered an exception and therefore, was not considered part of the final design. Trade-off studies for other design variables revealed:

- o OBIGGS sizing must be based on Military cold day operation
- o NEA5 was the optimal quality of the product gas
- o JP-4 was the worst case fuel when compared to JP-5 and JP-8 (greater dissolved oxygen)
- o Climb scrub remained best choice for dissolved oxygen removal. Other techniques examined were:
  - Aspiscrub
  - Ullage wash
  - Hybrid systems
    - * Ullage wash/climb scrub
    - * Aspiscrub/climb scrub
    - * Ullage wash/aspiscrub
    - * Ullage wash/climb scrub

The trade studies which did affect the baseline system and became part of the optimal stored gas OBIGGS were short or two minute taxi, inert taxi and repressurization schedule (Figure 4). Full time inerting during a short taxi (ground alert status) and an integrated combat turn (ICT) (fast ground turnaround) was a positive trade and was included in the optimal OBIGGS design. As shown in Figure 4, the OBIGGS is 20 pounds heavier for a two minute taxi because of less efficient scrubbing and shorter generation time. (The scrub nozzle efficiency is based on the ratio of actual dissolved gas removal to removal by an ideal nozzle. Typical scrub nozzle efficiencies are about 90%. However, in this study lower efficiency scrub nozzles were hypothesized to allow dissolved gases to be removed at more desirable rates. Presumably, less efficient scrub nozzles could be made by simply enlarging the holes in the nozzle but confirming test data have not been obtained). Alternative ground operating procedures could circumvent the requirement for higher scrub gas flows for fast response and fast turnaround operations. Scrubbing the fuel prior to parking on the tarmac for ground alert status provides inerting protection with no increase in system size. Scrubbing while refueling in an ICT would minimize the weight increase of the baseline system. Full time inerting during a normal (15 minute) taxi increased the system weight by 9 pounds (the aircraft was inerted for 100% of the mission compared with 84% for the baseline mission).

Most of the trade studies resulted in increased system weight, but the repressurization schedule for the F-16 in the combat mode allowed the system weight to decrease. Repressurization gas requirements and system weight decreased by 20 pounds with the variable demand regulator settings of a F-16 combat mode, compared to the constant demand regulator of the F-16 normal mode of the baseline (Figure 4). Also, the combination schedule shown in Figure 4, with the greater difference between the climb valve and the variable demand regulator reduced the system weight by 26 pounds.

**OPTIMAL STORED GAS OBIGGS** - Factors included in the optimal stored gas OBIGGS were a modified repressurization schedule, inerting for a short taxi time and ground alert status or an ICT. The optimal stored gas OBIGGS for the generic ATF aircraft assumed in this study had the following specifications (Figure 5):

| | |
|---|---|
| o NEA generation rate | .65 lb/min |
| o Advanced ASM inlet pressure | 60 psig |
| o Advanced ASM inlet temperature | 95°F |
| o NEA quality at sea level | 5% $O_2$ |
| o Storage requirement at 3000 psig | 50 lb NEA |
| o Fuel scrub efficiency | 25% |
| o Climb valve setting | +6.4 psig |
| o Demand regulator | 1.0 psig or 6.5 psia which ever is greater |
| o Dive valve setting | -0.75 psig |
| o Total system weight | 258 lb* |
| o Total volume | 7.4 $ft^3$* |

*Includes pre-cooler and ECS penalties and boost compressor.

This stored gas OBIGGS would provide full time inerting for most any mission (including inert taxi) including ground alert status (if the fuel is scrubbed prior to placing the airplane on alert status) and an ICT (if the fuel is scrubbed during refueling). This design would also prevent JP-4 from boiling at a maximum fuel temperature of 145°F.

**STORED GAS VERSUS DEMAND OBIGGS** - The stored gas and demand OBIGGS both require similar supply air conditioning equipment and perform in a similar manner. The basic difference is that the demand OBIGGS has a significantly larger ASM but does not require a high pressure compressor or storage containers. Factors affecting system sizing are summarized below:

| VARIABLE | EFFECT ON STORED GAS OBIGGS | EFFECT ON DEMAND OBIGGS |
|---|---|---|
| Increasing number of descents | Weight increases | None |
| Increasing altitude change during descents | Weight increases | None |
| Increasing rate of descents | None | Weight increases |
| Increasing mission length | Increases generation time | None |
| Decreasing taxi time | Weight increases | None |
| Increasing scrub gas requirements | Weight increases | None |
| Effect of 48-hour ground stand-by | None | Requires ground support |
| Reliability | Relatively low due to compressor | Relatively high (essentially passive) |
| Redundancy | None | Good (multiple units) |
| Impact on system maintenance and spares | Relatively high | Relatively low |
| Inlet Air Contamination | Sensitive | Less sensitive |

Survivability and vulnerability comparisons were also made. If the ASM, the high pressure compressor or the storage capacity of a stored gas OBIGGS is lost for any reason, the whole system is lost. However, for a demand system with multiple ASM modules, the loss of one module would allow the OBIGGS to provide inerting for most of the mission. The high pressure bottles in a stored gas system may pose a survivability problem due to the energy released in the event of a ruptured bottle.

## PROTECTION CONCEPTS COMPARISON

Existing fuel tank fire protection concepts, i.e. $LN_2$, Halon and explosion suppressant foam were compared to OBIGGS on the basis of degree of protection, weight, logistics support and life cycle costs (LCC). As shown in Figure 6, the lowest weight system is Halon 1301 and the heaviest is foam (largely due to the retained fuel). The stored gas OBIGGS was the lightest OBIGGS. The hybrid demand OBIGGS was lighter than the demand OBIGGS largely due to reduced ASM flow rate and the associated cooling equipment penalties. This system would satisfy the mission requirements of any mission analyzed. The Halon back-up would provide protection for the maximum descent rate.

The LCC comparison was for 20 years for a fleet and procurement of 750 aircraft with 600 being operational at any given time. The basis for comparison was the following cost categories:

- o Research and Development
- o Procurement
- o Production
- o Support investment
- o Operational and Support
- o Fuel penalties
- o Maintenance

The fuel penalties were determined from the weight penalties and power and bleed extraction for each alternative. The LCC results are summarized in Figure 7 in constant 1985 dollars. The Halon and foam systems had the highest costs. The fuel penalty was the major cost for the foam system and the cost of the Halon suppressant caused the cost of the Halon system to be quite high. The major cost factors for $LN_2$ were the flight line servicing support and the cost of the $LN_2$ itself. Both the stored gas and the demand OBIGGS had favorable life cycle costs. The fuel penalty, due to the system weight for the demand OBIGGS proved to be a major cost factor, but the inherent lower reliability of the stored gas OBIGGS resulted in higher operating and support costs.

## SUMMARY

The OBIGGS is very competitive with other aircraft fuel tank fire protection techniques for fighter aircraft fuel tank explosion protection based on weight, volume and life cycle costs. However, logistic factors alone may make OBIGGS the best choice for many future aircraft applications. The design of an optimum OBIGGS requires many complex trade-offs with a realistic assessment of aircraft mission and survivability requirements. The overall desired approach is a demand OBIGGS using an advanced permeable membrane air separation module.

## REFERENCES

1. Vannice, W. L. and A. F. Grenich, "Fighter Aircraft OBIGGS Study," AFWAL-TR-87-2024, January 1987.

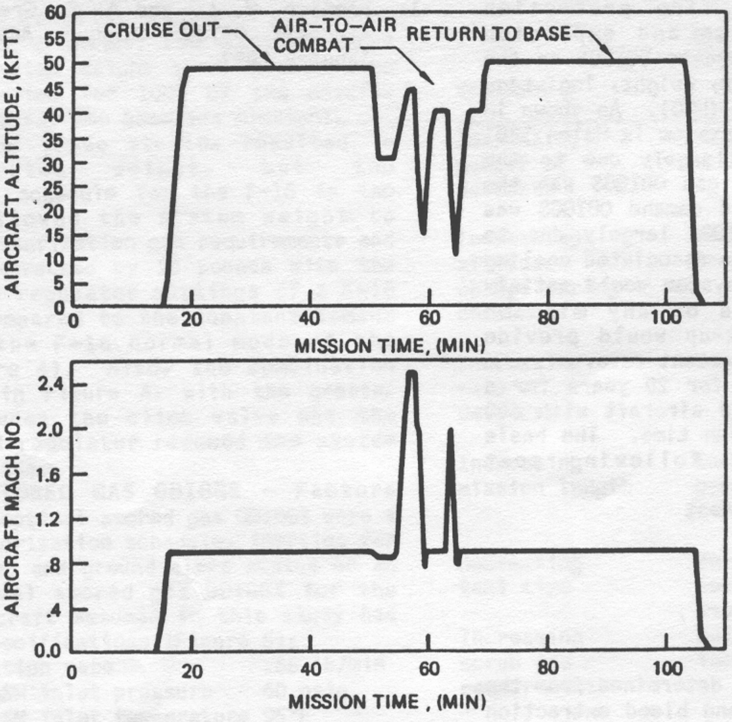

FIGURE 1. OBIGGS DESIGN MISSION PROFILE

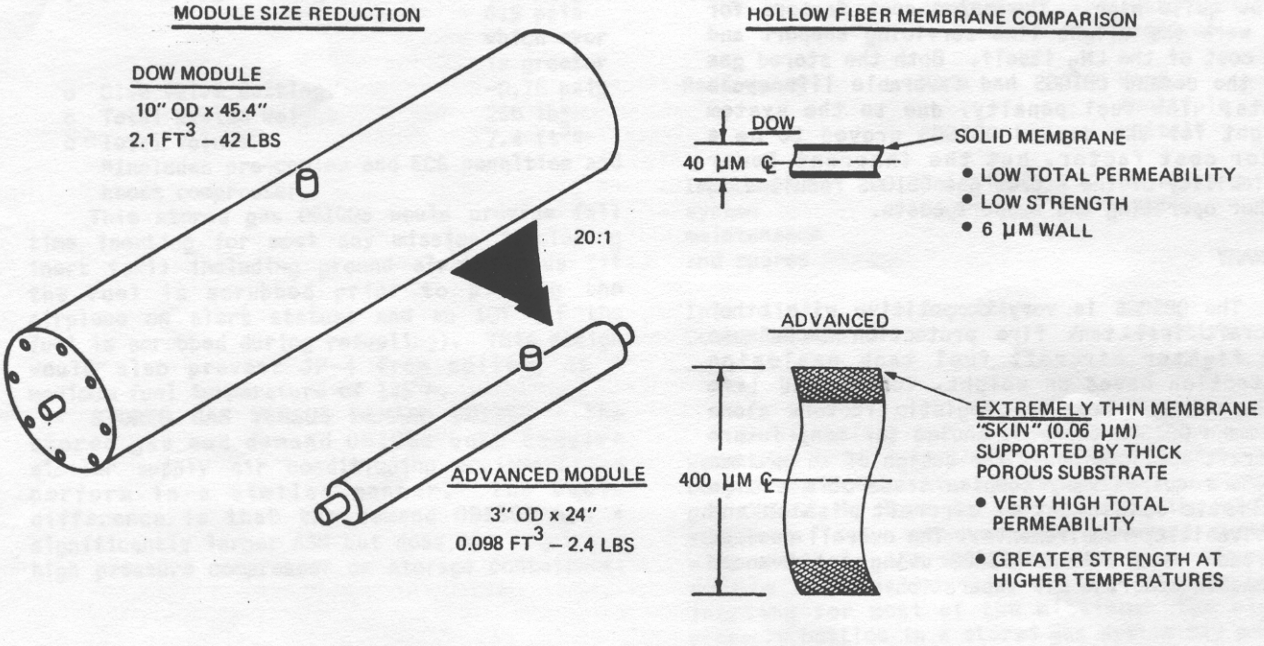

FIGURE 2. ADVANCED MEMBRANE IMPROVEMENTS

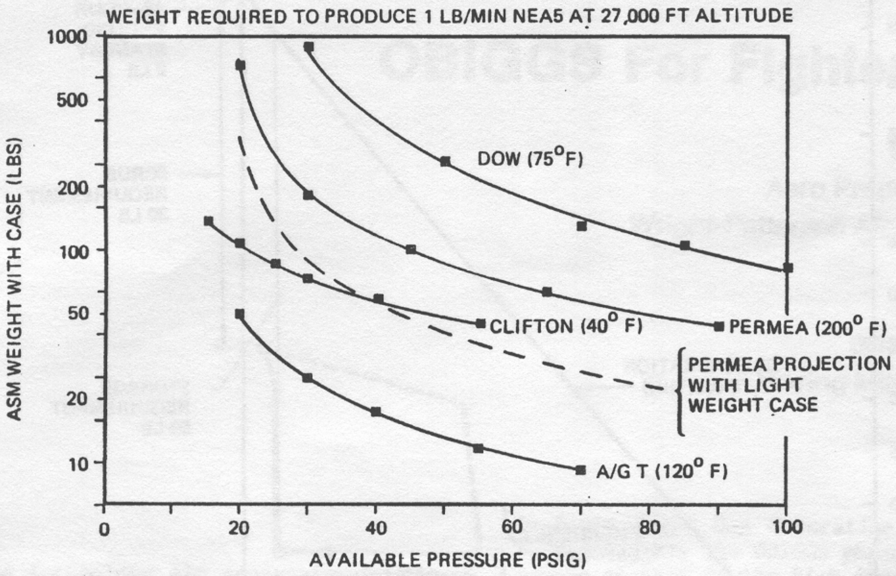

FIGURE 3. COMPARISON OF AVAILABLE ASM TECHNOLOGIES

| VARIABLE DESCRIPTION | SCRUB RQMT (LB) | REPRESS RQMT (LB) | SYSTEM WEIGHT CHANGE (LB) | OBSERVATIONS |
|---|---|---|---|---|
| Baseline<br>90% efficient scrub<br>15 minute taxi<br>inert 84% of mission<br>Repress schedule<br>F-16 normal mode<br>Climb valve<br>+6.4 PSIG<br>Demand regulator<br>+4.7 PSIG | 14 | 54 | - | |
| Two minute taxi<br>90% scrub efficiency | >30 | - | - | Scrub rate too high, did not analyze |
| 50% scrub efficiency | 21 | 53 | +20 | Scrub rate of 3.8 lb/min may be too high |
| Inert taxi<br>25% efficient scrub | 29 | 53 | +9 | Inert 100% of mission |
| Repress Schedule<br>F-16 combat mode<br>Climb valve<br>3 PSIG or 7.2 PSIA which ever is greater<br>Demand regulator<br>1 PSIG or 5.5 PSIA which ever is greater | 16 | 40 | -20 | Variable demand regulator saves repressurization gas |
| Hybrid schedule<br>Climb valve<br>F-16 normal mode<br>Demand regulator<br>F-16 combat mode | 14 | 35 | -26 | Greater difference between climb valve and demand regulator, greater repressurization gas savings |

FIGURE 4. TRADE—OFFS SUMMARY FOR STORED GAS OBIGGS

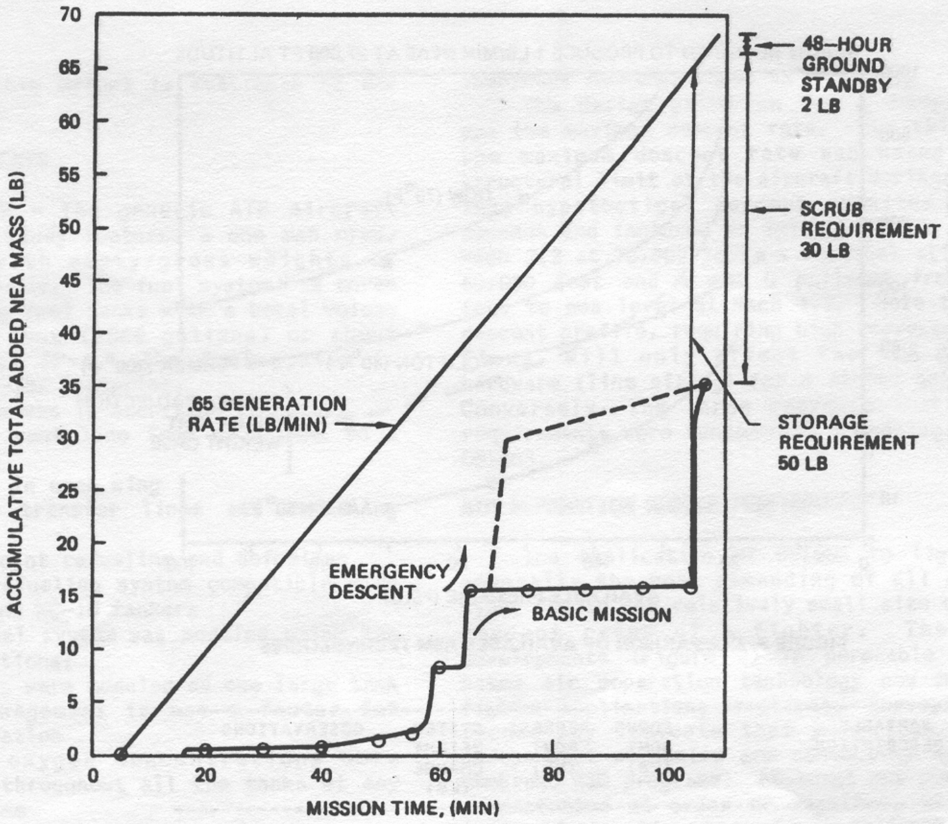

FIGURE 5. TOTAL GENERATION REQUIREMENTS FOR STORED GAS OBIGGS

| ASSUMPTIONS | STORED GAS | | DEMAND | | DEMAND & EMERG. HALON | | HALON 1301 | | $LN_2$ | | FOAM | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | •Optimal System<br>•Advanced ASM<br>•0.65 lb/min $NEA_5$ w/boost compressor | | •Current system<br>•Advanced ASM<br>•22 lb/min $NEA_{12}$ | | •Current system<br>•Advanced ASM<br>•15 lb/min $NEA_{12}$ w/boost compressor | | •Fuel time prot.<br>•One mission supply<br>•20% by volume repress. flow<br>•Fuel absorbtion 0.6 Lb/Min | | •One mission supply<br>•Same mass rqmt. as OBIGGS stored gas system | | •Fine pore<br>•50% void | |
| | Weight | Volume | Weight | Volume | Weight | Volume | Weight | Volume | Weight | Volume | Weight | Volume |
| System Components | | | | | | | | | | | | |
| • Bleed air supply | 5 lb | 0.1 ft3 | 90 lb | 2.0 | 64 lb | 1.8 ft3 | 0 | 0 | 0 | 0 | 0 | |
| • ECS (Δ) | 7 | 0.1 | 55 | 1.6 | 41 | 1.5 | 0 | 0 | 90(HX) | 0 | 0 | 0 |
| • IGG supply air conditioning | 6 | 0.4 | 35 | 0.9 | 21 | 0.8 | 2 | 0.1 | 0 | 0 | 4 | |
| • Compressor, motor, intercoolers | 83 | 2.5 | 0 | 0 | 30 | 0.2 | 0 | 0 | 0 | 0 | 0 | 0 |
| • Storage bottle & fittings | 80 | 3.7 | 0 | 0 | 20 | 0.2 | 42 | 1.2 | 54 | 1.6 | 0 | 0 |
| • IGG | 14 | 0.4 | 143 | 3.4 | 64 | 1.6 | 0 | 0. | 0 | 0 | 0 | 0 |
| Distribution system | 38 | 0.2 | 42 | 0.2 | 39 | 0.2 | 17 | 0.1 | 12 | 0.1 | 0 | 0 |
| NEA, halon, LN2, or foam | 25 | 0 | 0 | 0 | 30 | 0 | 107 | 0 | 77 | 0 | 282 | 5.4 |
| Retained fuel | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 452 | 0 |
| Total | 258 lb | 7.4 ft3 | 365 lb | 8.1 ft3 | 309 lb | 6.3 ft3 | 168 lb | 1.4 ft3 | 233lb | 1.7ft3 | 738 lb | 5.4 ft3 |

FIGURE 6. PROTECTION SYSTEMS COMPARISONS WEIGHT SUMMARY

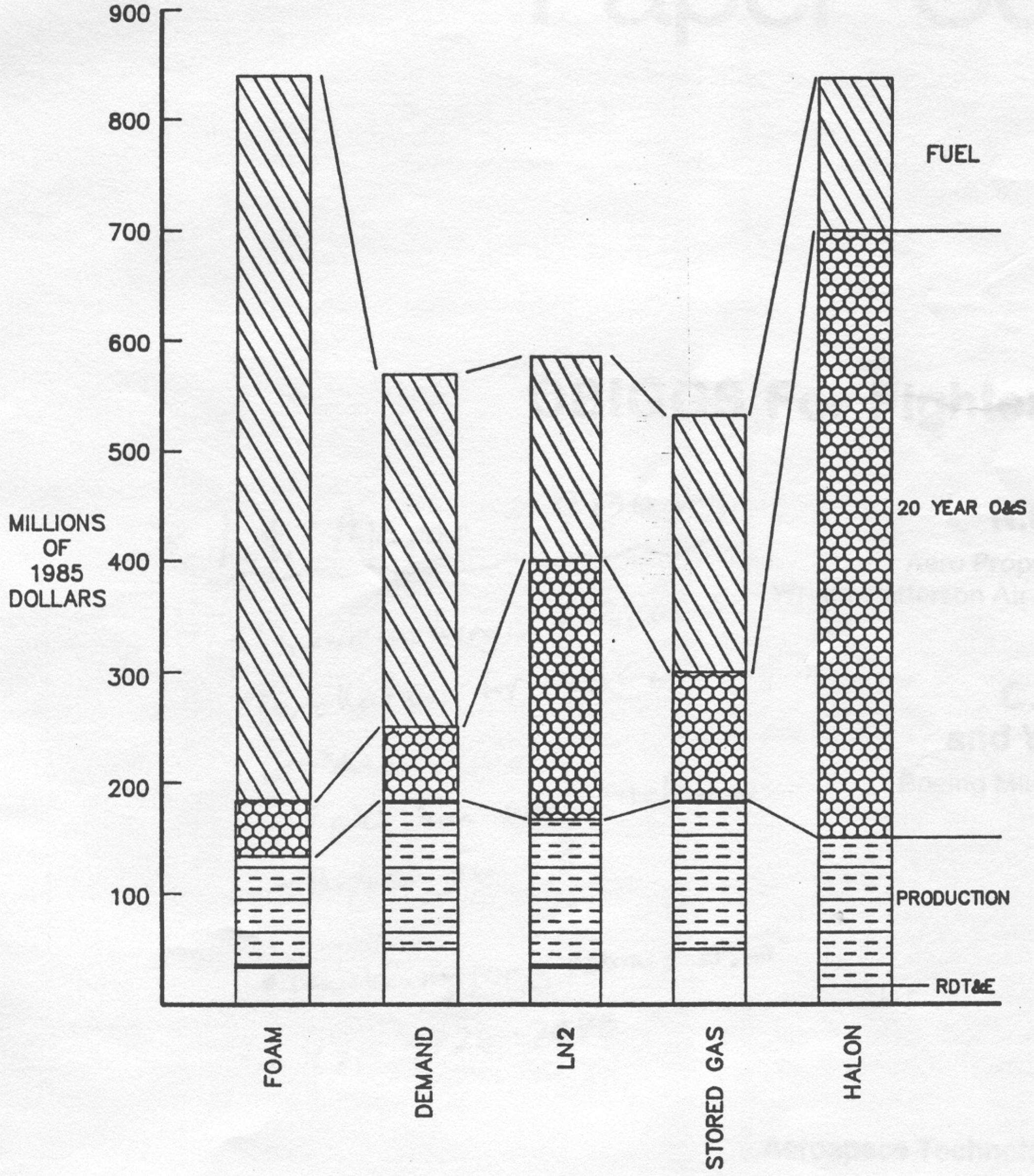

FIGURE 7. LIFE CYCLE COST COMPARISON