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ABSTRACT

This paper discusses functions which will require support from the on-board computer system during advanced manned missions. In addition to present-day functions, such as guidance, navigation and attitude control, the computer system would provide capability for: 1) monitoring, confidence testing, and diagnostic testing for spacecraft systems and experiments; 2) inflight crew training with simulations; 3) control and data management for experiments; 4) displays for flight and experiment operations; and 5) G&N of unmanned probes launched from the mother craft.

It is concluded that: 1) The functions (G&N, attitude control) which originally justified using on-board computers are no longer the pacing factors in determining many computer system characteristics; 2) Mission complexity will force the crew to make extensive use of computer system support; 3) The growth of computer usage in spaceborne scientific experimentation will parallel the historical surge evident in ground-based experimentation; 4) Increased functional requirements will result in a greatly increased number of I/O channels, increased high speed memory, the addition of off-line bulk storage, and more powerful processing capability, regardless of the specific system configuration; and 5) The amount of on-board software required for a manned flyby mission will be large relative to manned missions heretofore.

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FROM: E. L. Gruman
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TECHNICAL MEMORANDUM

1.0 INTRODUCTION

In the Apollo program the spacecraft computers are used for the functions of: guidance, navigation, attitude control, operation of simple displays, astronaut-computer communication, and computer-ground communications. They also run tests on themselves and the G&N system. Beyond Apollo, the increasing complexity of missions, and advances in computer technology, will undoubtedly result in a lengthening of the list of functions.

This paper discusses various functional requirements for spacecraft computer systems on advanced manned missions. A planetary flyby mission shall be used as an example mission for the purpose of this discussion. Nevertheless, the discussion will be applicable, to varying degrees, to long duration earth orbital, planetary landing, double flyby, and other manned missions.

Emphasis is placed on requirements which are new, i.e., not expected to be found on missions through Apollo. It is assumed that the spacecraft must be capable of entirely independent operation, regardless of whether the spacecraft or ground has prime control for the various mission operations. No attempt is made to delineate a specific computer system configuration, although certain gross system characteristics can be inferred.

2.0 EXAMPLE MISSION

The planetary flyby mission used as an example here is assumed to begin with assembly and checkout of a spacecraft and injection vehicle in earth orbit. The spacecraft includes a large Manned Module (MM) in which the astronauts normally carry on their activities during the trip, and a small Earth Entry Module (EEM) for the final return to Earth. After injection toward the planet, a few midcourse corrections are made. In transit, experiments in space physics, behavior, and physiology are conducted. Astronomical observations are made using a large telescope. A few days before planetary encounter, several (about six) unmanned probes are ejected from the spacecraft and guided toward the planet. The probes may include orbiters, slow-descent atmospheric probes, and soft landers. The probes communicate at high data rates with the mother spacecraft for a short time before and after periapsis.

On-board the spacecraft, remote measurements of the planet are made using various portions of the electromagnetic spectrum. A large number of high resolution pictures are taken using the large telescope. Data is transmitted to Earth at rates up to one megabit per second from injection until a few weeks after encounter. The maximum rate diminishes to a low of approximately seventy kilobits per second. This low rate lasts for about a month, then returns to one megabit per second. There may be a period on the return leg when the sun lies between the spacecraft and Earth; this would cut off communications with Earth for as long as two months. The return leg of the mission is used to transmit data collected during planetary encounter to Earth and to perform experiments similar to those on the outgoing leg. Earth entry will occur some one and one-half to two years after injection.

3.0 REQUIREMENTS FOR FLIGHT OPERATIONS

3.1 Monitoring and Testing On-board Systems

Three levels of testing will be required for conducting flight operations: monitoring - an essentially continuous check of certain system parameters; confidence testing - a more detailed check of system parameters before certain crucial events; and diagnostic testing - a still more detailed check of a system whenever it is found to be faulty.

Checkout at these levels is not restricted to inflight needs but is required as well in certain phases prior to launch. Use of an integrated testing concept[1] in which certain prelaunch and inflight tests are carried out in a common manner by essentially the same automatic equipment appears desirable, both for economic reasons and to maintain continuity of testing. The on-board computer system is the natural candidate for the job.

There are other arguments for using the on-board computer system for checkout. Monitoring system status for long periods of time is a job done poorly by humans and, even worse, is a waste of precious resources.[2] Confidence and diagnostic testing, though higher order tasks than monitoring, are also candidates for automation in order to obtain faster testing with less chance of human error. This is particularly true at hectic times in the mission or if multiple failures occur.

The use of a computer for testing provides the storage media, computational capability, and logical capability for making comparisons and indicating trends with both accuracy and repeatability. Furthermore, the test points and much of the checkout software will already exist from prelaunch requirements. It will also be desirable to have an automated system on board which can assist the ground in determining the status of the spacecraft, especially if part of the crew becomes incapacitated.

Astronauts will control the automated checkout system via a checkout station which will have a keyboard, displays, and communication link with the central computer system. Ordinarily, only summaries of system status will be presented on the displays. Upon request, the astronaut will be presented with more detailed information on any system. He will be able to ask for present, former, or nominal values. He will also be able to initiate confidence and diagnostic tests. His overall capability will be somewhat like that at launch system consoles during an Apollo countdown. The MADAR (Malfunction Detection and Recording) System, an automated inflight checkout and maintenance system being developed for the C-5A transport,[3] is another precursor of the type of system envisioned.

In Apollo, the ACE (Acceptance Checkout Equipment) spacecraft test points are automatically checked on the ground. Only a restricted set of these points is used on board because of the very limited use of inflight maintenance. In contrast, an interplanetary spacecraft will probably have all of its "ACE" points available in flight as well as preflight. Some of the points used for diagnostics and all of those used for monitoring and confidence testing will probably be wired into the automated checkout system. The rest--those of improbable use due to limited system usage or lack of criticality--will be accessible by being plugged into a portable interface with the computer.

How many test points will there be? On one hand, the increases in system size and sophistication and the addition of new services will tend to increase the checkout requirements over Apollo. On the other hand, the increasing capability per unit size of electronic devices and other system building blocks will tend to reduce the overall number of points to be tested. The authors' speculate that for a mission such as the 70's flyby example, one can expect a factor of two to five increase over the number of Apollo ACE CSM test points. This implies approximately 2000 - 4000 test points for the MM systems. Diagnostic test points would make up about three fourths of the total number.

Three broad classes of diagnostic approaches are foreseen: 1) those for digital systems (automated); 2) those for analog systems (automated); and those for basic building blocks (semi-automated). Just as they require more test points, digital equipments generally require more complex diagnostic routines than do analog equipments since they are generally capable of many more operational states. Thus, elaborate diagnostic routines are foreseen for systems such as up and down data links, the computer system itself, and the computer interface equipments. Certain digital/analog hybrid subsystems will also require rather elaborate diagnostic routines.

The totality of diagnostic programs will require a significant amount of bulk memory space. For example, the Apollo ACE programs use tens of thousands of words for checkout of a lunar landing mission spacecraft. A planetary flyby spacecraft would require somewhat greater storage for the totality of its checkout programs.

The discussion thus far applies primarily to an MM where the crew normally carries on its activities. It is recognized that an EEM would be checked out prior to interplanetary injection and prior to Earth landing. Its checkout equipment may be partially self-contained, partially contained in the MM. The MM computer system may therefore have to bear part of the load of EEM checkout as well as its own. However, for most of the mission, EEM checkout will not ordinarily be of concern.

3.2 G&N, Abort Guidance, and Digital Autopilot

Guidance, navigation, and abort requirements obviously depend heavily on the type of mission involved. For planetary flyby missions, the G&N computation requirements would not be substantially higher than those required for a lunar flyby, except in the vicinity of the planet, where probe guidance (briefly discussed later) is necessary. There would be opportunity for early return by abort only while the spacecraft is significantly influenced by the earth's gravitational field, which is less than one percent of the mission duration. Abort G&N algorithms would be of the same order of complexity as the abort algorithms used for a lunar flyby.

A significant impact upon advanced computer systems could result from the use of strap-down inertial measurement units (IMU's), which are candidates for planetary mission use because of reliability per unit weight and power considerations. There are indications that strap-down units could increase the on-board G&N computation load by as much as a factor of five to ten with respect to the calculations required using a gimbaled IMU, although use of a digital autopilot tends to lower this factor slightly. Both gimbaled and optical platforms are also possibilities. Either could well be used, if not in a prime role for the entire mission, then as prime for a particular mission phase or as backup.

3.3 Displays

Currently, the interior of a spacecraft resembles an airplane cockpit: a profusion of dials, lights, and switches, each with a unique function. For the most part they are connected to sensors with little or no information processing en route. Pilots eventually learn to live with this display jungle, though non-pilots are usually staggered by it. The situation could get worse with the more numerous and complex systems expected on advanced missions.

One source of relief would be to display less subsystem data with the aid of the previously discussed automated checkout system. Another approach would be to combine information from various sensors into integrated situation displays like those recently developed by Army-Navy research for aircraft use.[4] In one such display system, data is collected from the gyros, radars, air data computer, compass, instrumentation landing system, and fuel flowmeters. The central digital computer system processes the information and provides the outputs to run a vertical situation display and a horizontal situation display.

A version of the vertical situation display, made by Kaiser Aerospace and Electronics Corporation, is currently operational in the Grumman A-6A Intruder. This "contact analog" display shows the command flight path as a highway in the sky. The highway is in proper perspective as viewed from the current position of the aircraft. The pilot flies his command course simply by trying to stay on the highway. Other features include a distance scale, the aircraft attitude in three dimensions, and symbols for a target and a weapon release point.

In a second mode, the display projects a synthetic 3-D view of the terrain ahead of the plane, using range, altitude and azimuth information from the radars. The terrain is shown as ten vertical slices at various ranges (1/4 mile ahead, 1/2 mile ahead, etc.). Each slice shows terrain height vs. azimuth at that range, so that the overall effect is one of looking at a three dimensional contour map. Tests show that pilots can follow terrain contours of the radar display more accurately and with more confidence than with visual references in clear weather. The radar sharpens terrain features, and accurately measures range which the eye only estimates. Pilots like these displays.

The flight display puts a light incremental computation load on the central computer, since most of the displayed data must be calculated regardless of the type of display used. The amount of additional computer memory space which may be charged to this particular display is estimated at less than 1000 words.

It seems reasonable to anticipate variations of the above integrated situation displays which would assist rendezvous, earth entry, attitude control, and virtually all other piloting function aboard a manned spacecraft. For example, consider a manually controlled rendezvous with another vehicle which has an extremely unfavorable lighting background. A display showing the vehicle in perspective, some range markers, the desired rendezvous trajectory, and appropriate command information would be of considerable aid to the pilot and thereby increase reliability in a critical situation. Other integrated displays might be used for projecting entry corridors as three dimensional paths, or in simulations used for onboard crew training.

In addition to these somewhat exotic displays, there will be more mundane CRT or electroluminescent (EL) displays for showing such things as X-Y plots and alphanumerics. For example, the automated checkout system will use these displays. Others will be associated with experiment control and data management. The Apollo spacecraft uses numeric EL displays for showing selected outputs from the AGC.

The role of the computer in all of these various onboard display systems is obvious: it collects and formats information from various sensors; stores and fetches data; performs necessary computations; and composes appropriate data into the various presentations by commanding the appearance and positioning of symbols, waveforms, and other types of graphics. In spite of the inference one might draw from the vertical situation display example presented here, the load on the computer for driving displays may vary over a very wide range.

The MTBF's of present integrated situation displays are estimated at several days to several weeks--too low for planetary missions. Anticipated improvement in CRT and/or EL technology will significantly increase these MTBF's. The fact remains that most of the elements of the present display jungle have the inherent reliability advantage of the simple over the complex and of not putting all the eggs in one basket. Until the more sophisticated displays are proven reliable, they will probably be backed up by a reduced set of "simple" displays.

3.4 Astronaut-Computer Communications

The Apollo astronauts communicate with the Apollo Guidance Computer (AGC) using a keyboard with buttons for: numbers 0 - 9, +, -, VERB, NOUN, CLEAR, STANDBY, KEY RELEASE, ENTER, and RESET. The astronauts consult a code book and punch in digits representing verbs, nouns, or data. The verbs are simple commands to the computer, such as "display (noun)," "monitor (noun)," "load (noun)," The nouns are various parameters such as velocities, angles, rates, positions, times, etc. The computer communicates with the astronauts via a simple numeric EL display and a set of status lights. Almost the entire computer-astronaut dialogue centers around guidance and navigation.

The expanded set of computer functions on advanced missions will require more frequent, more inclusive, and more sophisticated man-machine communications than in Apollo. A premium will be placed on speed and accuracy of communications and on minimizing the tremendous learning burden of the astronauts. The improved displays suggested in the preceding section will be one source of aid. Another will be higher level input languages. Research is needed to define either a general spacecraft command and control language or a group of function-oriented languages for the astronaut-computer dialogue. Reasonably detailed diagnostics of input programs should also be provided. A high level language package plus increased diagnostic capability imply the availability of additional high speed memory space.

Another improvement will be to enlarge the keyboard and have individual keys for frequently used words, with less frequently used words inserted via a general set of alphanumeric keys. The choice of words to be considered "most frequent" might be left to the user and allowed to vary from person to person and station to station. All commands could still be initiated from any keyboard.

Optional hard copy of inputs or outputs would be another desirable feature. Also, punched or magnetic cards might be used for storing frequently used programs. The card would be inserted into a computer input device, similar to card dialers used with telephones, in lieu of punching buttons whenever the program is desired. Voice input devices might also become feasible for some portion of the input repertoire.

3.5 Inflight Crew Training

> "During a several month interplanetary voyage, crew members could lose some of the skill they have developed in such maneuvers as earth atmosphere re-entry."(5)
>
> Astronaut Alan B. Shepard

Planetary flybys will put at least one to two years between the time an astronaut last flew (or practiced in a full scale simulator) an earth entry and the time he must do so again. The intervening time plus the physiological and psychological demands of the mission will tend to degrade his ability to perform the task. Various other on-board tasks will have smaller but still significant intervals between practices. Examples are planetary photography at close range, targeting and guidance of probes, and on-board planetary encounter experiments.

The astronauts must somehow maintain their skills in these tasks, either by live practice runs or simulations. Ideally, they should use the same controls, displays and systems for practicing as in actual operational usage. However, there is a school of thought that one should not take flight-critical controls and displays off line for simulations during a mission. Moreover, introducing simulation modes (with switches and additional input and output paths) may lower system reliability.

We therefore anticipate the existence of an on-board training, simulation and behavioral research station. It would have displays and controls which can assume different configurations to simulate different crew stations. It would use the computer system for controlling real time simulations, storing norms, simulating certain systems, evaluating results, and compiling subject profiles. The facility would have the following uses:

1. Training. This is required to maintain crew skills which are not frequently used.

2. Crew reassignments. Each astronaut will be a specialist in some areas and cross-trained in others. At some point in the mission, perhaps due to the incapacitation of some other crew member, it may be desirable or necessary to

reassign an astronaut from his original specialty to another. The equipment and software used for "routine" training might suffice, though some additional "teaching machine" capability may also prove to be desirable.

3. Checkout of new procedures. These may be established by the flight crew or ground during the course of the mission [The mission will be of such duration that even state-of-the-art advances are possible.] This function requires the ability to insert large new programs into the computer from ground or smaller ones from on-board.

4. Behavioral research. In addition to the biomedical monitoring of the astronauts, certain behavioral studies will take place. These will consist of tests of reaction-time, decision-making and problem solving. The results of these tests wll be correlated with biomedical data to indicate the "condition" of the astronauts at various points in the mission. Since these behavioral studies will require the use of displays and controls, it should be possible to use the facility for behavioral experiments as well as for simulation and training.

The simulations used in conjunction with this facility would be major users of computational time when running. They could be among the largest programs on board. The Apollo Mission Simulator and LM Mission Simulator programs each run greater than 100K words. Though not necessarily representative, they indicate how large these simulations can become.

4.0 EXPERIMENTS REQUIREMENTS

4.1 On-board Experiments

"Nuclear instrumentation is undergoing revolutionary changes because of [the] rapidly increasing use of stored-program computers by experimentalists in nuclear-structure laboratories."

John V. Kane

"In the high energy physics laboratory the most remarkable development that has occurred in the last five years has been the introduction of the digital computer as an active part of the experimental apparatus."

George W. Tautfest

Both of these quotes were taken from the July, 1966 issue of "Physics Today" and indicate the effect computers have had on ground-based experimentation. It is likely that space-borne computers will have a similar effect on space experimentation within the next decade when one considers that they have been virtually unused thus far and that the number and complexity of experiments are increasing. For example, the particles experiment on Explorer I measured omnidirectional intensity of particles of any type. On OGO-E, the particles experiment will measure directional characteristics and intensity as a function of particle energy and type.[6] Several uses of computers in on-board experimentation are suggested in the following sections.

<u>Experiment Checkout and Calibration</u> -- It is estimated that there will be about 30-40 major pieces of experimental equipment on-board a flyby spacecraft in addition to about forty carried in the unmanned scientific probes. There would also be a large (40") telescope with its own attitude control, photographic and TV systems.

About one third of the on-board experiments and the telescope system must be monitored and occasionally tested or calibrated throughout the mission, much in the manner of spacecraft systems. Another third of the on-board experiments, the forty experiments carried in the probes, the various subsystems of the probes, and the flyby photography and TV systems must all be tested, and calibrated if necessary, shortly before planetary encounter. This may involve on the order of one to two thousand test points.

The checkout and calibration tasks should be automated to the fullest extent possible for reasons similar to those given for automating spacecraft systems checkout (obtain speed and accuracy, reduce crew workload, avoid human error, etc.). The precision possible with a computer system will be of even more importance for these tasks than for testing of spacecraft systems because of the generally greater precision required by scientific measurements compared to operational engineering measurements (G&N systems excepted).

As in testing, the use of the computer system for calibration will permit the use of complicated or exhaustive schemes which might not otherwise be used. This, plus the accuracy and repeatability of the computer, the ability to record steps in the calibration process, and the presence of man, will result in greater confidence in the calibration of the experiments--an important advantage over present experimentation.

Experiment Control -- At various times in the mission experiments must be turned on, have their sensors exposed, be run through a warm-up sequence, be coordinated with other experiments, undergo cyclic changing of operational modes, etc. Although most of these functions could be implemented with simple programmers, they are candidates for computer control in order to allow flexibility in flight. Building a programmer with enough flexibility to arbitrarily change the timing and sequencing of experiments may be less desirable than building a wired interface with the computer system, using a modest amount of computer time and memory space, and keeping the flexibility in the software.

A more complex type of control than sequencing may be needed for experiments such as patrolling for solar flares. In this experiment, the sun will be monitored for about half of the planetary mission using telescopes, X-ray, UV, visible and other electromagnetic sensors, cosmic ray and solar proton sensors, etc. While the crew may occasionally or even regularly monitor the sensors, it does not seem reasonable to spend a man-year for this purpose, since the flares occur only about 0 - 20 times per year. Nor can one rely on Earth to warn that a flare is occurring. The visible portion of a flare lasts from several minutes to one hour, whereas the communication time for transmitting the warning from earth to spacecraft will be in the order of 0 - 30 minutes; the flare or its beginning might be missed entirely.

It would be economical in film, bit storage, and man-hours to have a system which samples the sensors at a low rate until something unusual occurs, then alerts the astronauts, increases the sampling rates and photographic repetition rates, and brings on-line any sensors which may have been inactive. The computer system would be used to discover the "something unusual," perhaps using pattern recognition techniques to determine an unusually bright area on a TV picture of the sun. The computer system would command the initial response. This overall scheme represents one form of data compaction by computers.

Several experiments, including the above, will require accurate pointing and holding to targets on various heavenly bodies. Calculations for these functions may require data from the on-board autopilot and G&N system, the telescope attitude control system and ephemeris tables.

Experiment Data Management and Displays -- The astronauts themselves will have an important role in the checkout, calibration and routine control of the experiments. In addition, they should have some capability to take advantage of discoveries, explore anomalies, redirect experiments in case of failures or mistakes, and select data for transmission to the ground.

To perform these tasks the astronauts must be able to sample, in real or near-real time, data from any of the experiments being conducted. Though this may not always be possible, it should serve as a goal. They must then be able to process the data with the aid of the computer system if necessary. Processing may involve curve-fitting, computation of statistics, statistical filtering, correlating data from several experiments, solving systems of equations, and an extremely wide range of other possibilities.

Both raw and processed data should be capable of being displayed in a variety of alphanumeric and graphic formats. Display options should include symbols, histograms, X-Y plots, waveforms, and scatter diagrams. The astronauts should also be able to display data from several related experiments simultaneously and to request a priori expected results to be displayed alongside actual results.

4.2 Probes

In our example mission, the crew of the flyby spacecraft must check out and count down the approximately six scientific probes about one week prior to encounter, using the computer system for automated testing and sequencing. About three of the probes will be of the complexity of Lunar Orbiter or Surveyor; the other three will be relatively simple atmospheric probes. All would be launched within a period of a few days.

After injection toward the planet, the probes will be tracked from the spacecraft by radar and optical techniques. Before landing (or going into orbit), the probes receive one or two midcourse corrections from the spacecraft. The corrections are based on the continually improving knowledge of the spacecraft's trajectory relative to the planet. The trajectory improvement is based on inputs from the on-board sextant and telescopes and from earth-based continuous tracking.

Thus, the spacecraft must act as a spaceborne tracking and flight control facility while at the same time navigating for itself. It has been estimated that the spaceborne computation load for probe guidance will be several times that of the Apollo LM descent guidance, the most demanding of the Apollo guidance programs.

It is not clear to what extent guidance computations for the various probes would overlap in time with one another and with other tasks. It is clear, however, that the probe guidance tasks will be of extreme importance and will be demanding attention at one of the busiest, most critical times in the mission.

5.0 RELIABILITY REQUIREMENTS

The heavy dependence upon the computer system suggested in this paper presumes extremely reliable hardware and software. In Apollo, the guidance computer is required to have a certain MTBF. A computer system for interplanetary missions will also have MTBF requirements, but in addition will be required to absorb (at various levels) certain malfunctions without hindering performance, and certain other malfunctions without complete loss of performance. Considerable study is being given to hardware reliability, and techniques are rapidly becoming available to meet these enhanced requirements on hardware.

The AGC software is required to produce appropriate outputs under allowable input conditions. This general software "quality" requirement, already difficult to achieve, will tend to become even more elusive in future missions. The housekeeping functions introduced by redundancy and switchable configurations as well as increased I/O will significantly complicate the package of programs relative to the AGC software.

In studying the software quality control problem of Project Apollo, it was concluded that the use of strong management procedures including tightly controlled documentation was the most valuable approach available.(7) Producing detailed software documentation has a most desirable by-product, that of forcing the thinking out of program possibilities. This tends to eliminate problems due to logical inconsistencies. It appears that strong management control will remain a valuable approach for interplanetary missions. The general problem of software reliability is ripe for new approaches.

6.0 CONCLUSION

The following inferences can be drawn from the above discussion:

1. The functions which originally justified bringing a computer on board a space vehicle (G&N, attitude control) will no longer be the prime factors in determining characteristics of the computer system. The new functions, automated checkout, flight crew training, expanded displays, and on-board experiment control and data processing, will force the future on-board computer system to have the capability to efficiently perform character manipulations as well as mathematical calculations.

2. The complexity of spacecraft flight operations and scientific activities will alter previous mission management concepts. The crew will make extensive use of the automated system centered around the computer(s). This will require highly efficient astronaut/computer communications. More sophisticated displays and input languages than those being used in Apollo will be required to accomplish this.

3. The growth of computer usage in on-board experimentation will parallel the rapidly expanding usage in ground-based experimentation. This will impose significant requirements on both the memory and processing capability of future on-board computer systems.

4. The increased functional requirements will result in a greatly increased number of I/O channels, an increase in high speed memory by a factor of two to ten, the addition of off-line bulk storage memory, and a more powerful processing capability than is presently available in Apollo. These characteristics will require either a very fast central processor or a multiprocessor system.

5. The amount of on-board software required for a manned flyby mission will be large relative to manned missions heretofore.

There are various functions in addition to those discussed in this paper which may be candidates for use of the on-board computer system. For example:

- Spacecraft housekeeping, such as automatic balancing of solar heat loads by attitude control.

- Communications management, such as routing messages between spacecraft systems, experiments, probes and ground, and pointing spacecraft antennas.

- Medical diagnosis

- Data reduction and compression, in addition to controlling experiment sampling rates as in solar patrols. (This is not foreseen as a vital function because of the expected 10^6 bits/sec. transmission capability on board.)

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Attachment
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