Developments Associated with Advanced Commercial Aircraft Crew Requirements

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Increasing airline traffic congestion and advancements in aircraft performance and complexity are imposing greater demands on the flight crew. This undesirable trend may be countered by a more scientific approach to the over-all integration of cockpit design efforts in terms of instrumentation and displays, avionic systems, crew visibility, and flight controls. In addition, the influence of advanced simulation techniques, early vendor participation, and the widest use of U. S. and international development facilities and research can assist in insuring an optimum cockpit design. The design approach taken with a supersonic jet transport was aimed at achieving improved cockpit design by use of the foregoing techniques, and the results are described. Lessons learned from the development process of present-day transports and the more advanced approach to the SST will be incorporated into design efforts to be applied to a second-generation jet transport, and this proposed approach is also outlined.

Introduction

ADVANCES in airplane design technology which have occurred in recent years—jet engines, new structural materials, and manufacturing techniques—have offered the commercial aircraft designer opportunities for improvements in aircraft speed, payload, range, and economics. Accompanying the technological advances in design has been a rapid and radical increase in traffic density and also strong pressures to minimize the influence of weather on regularity. These two factors of advances in design technology and increased traffic density have increased the need for the use of advanced subsystems, especially in the avionic and controls disciplines. In the primary controls area the trend is toward full power with the consequent system redundancy, together with the increasing requirement for stability augmentation. Advanced communication systems are becoming available, a demand for more flexible and accurate navigation aids, including vertical navigation, is arising, and all-weather landing systems are becoming widely accepted as standard airborne equipment by most of the major airlines.

All of the aforementioned factors indicate a trend toward increasing crew workload, particularly in the already critical segment of flight: the terminal area. Although airline crews, through improved training, have done an outstanding job of coping with the demands made upon them, a determined effort to reduce these demands is clearly needed for commercial aircraft of the next generation.

The evolutionary nature of human behavior inevitably moderates rapid change in cockpit instrumentation and operational techniques, but unless a resolute effort is made to insure the continuing reasonableness of crew workload, the gap between requirements and capability could widen to unacceptable limits. The objective of the programs described in this paper is an attempt to apply all available knowledge and technical capability to prevent this from happening and, if possible by better understanding of the problem, to effect progressive reductions in crew workload as a basic airplane design parameter. The establishment of a logical systems engineering approach is believed to be essential to achieving this goal.

Systems Engineering Approach to Crew Requirements

The systems engineering approach requires that an orderly and, as far as possible, scientific consideration be made of all the interacting elements of the total system. The system in this case is defined as the over-all operational environment of the commercial transport airplane which includes the influences of weather, other aircraft movements, air traffic control, and the physical characteristics of the terminal facilities. The subsystems aspects of the aircraft itself include the flight crew, the aerodynamics, the performance and handling qualities of the aircraft, and the influence of the various subsystems in the airplane which affect the aircraft's functioning within the over-all systems environment. The approach to be taken involves at least the following steps: 1) Define the system. 2) Define the problem, breaking the over-all problem down into elements which can be clearly identified and defined. 3) Develop requirements: identify requirements that must be fulfilled in order to solve each element of the problem and establish the interrelationships between the various parts. 4) Synthesize the system: develop methods of meeting the requirements. 5) Analyze the system: evaluate proposed systems under simulated and/or real life conditions. 6) Select the best candidate systems. 7) Reiterate the process until the optimum configuration is determined.

As this list illustrates, this approach is one in which, as far as possible, fact is substituted for opinion and in which the interrelationships between elements of the total system are developed in a logical and orderly fashion. One of the major problems of commercial aviation today is that the total system is becoming so diverse that adequate appreciation of and study by one group of people is becoming increasingly difficult to accomplish. Since the aircraft element of the system plays a primary role, it seems logical and natural for the system engineering concerned with crew requirements to be carried out by the airframe manufacturer. On the other

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hand, the manufacturer cannot completely accept the responsibility and expense associated with all the research and development activity which will influence the crew requirements of his particular airplane design. He can, however, be the coordinating authority for this task, and it is logical that he should do this, since he bears the initial responsibility for meeting the safety and performance requirements of the airplane which he manufactures. He is also probably in the best position to achieve a definition of the problem. It would obviously be outside the scope of this paper to discuss in detail the individual steps of the systems engineering approach required to evaluate and improve crew workload conditions. The following are examples of some of the elements of the problem which must be covered in order to achieve satisfactory results.

What Does the Crew Need to Perform Its Tasks?

The crew require controls, displays, monitors, visibility, and adequate working conditions. All of these factors influence crew workload, and must be analyzed both separately and from the interrelationship viewpoint in order to have a logical understanding of the crew requirements. Human factors studies obviously play an important part in this aspect of cockpit design, and several good analytical methods have been evolved to assist in a more scientific analysis of the pilot's needs and reactions.

What Is the Environment under which the Crew Must Operate the Airplane?

Environmental factors that affect operation of the airplane are weather, air traffic control (ATC), schedule, and other traffic. Here is an example of elements of the over-all system problem which are outside the scope of the aircraft manufacturer to determine by himself, and it is probably in this area that the maximum cooperation is needed with national and international authorities capable of providing inputs to enable definition of the environment to be best made. This area is probably the least well defined of all the variable influences on the performance of the aircraft.

Special Factors Affecting Crew Performance

These special factors are grouping of instrumentation, arrangement of controls, and operational procedures. This is an area which is influenced greatly by the particular airline operating the aircraft. There is good conformity of opinion in this area generally but as airplane systems become more sophisticated there will be a greater need for agreement between the various airlines concerning these factors. Again a better comprehension of the human factors aspects would assist.

General Influences on Crew Workload Level

These influences include effect of larger and more complex aircraft, requirements of specific and more rigorous operational procedures, monitoring of more complex and larger number of airborne subsystem equipments, requirements imposed by lower weather-minima operations, both takeoff and landing, requirements of noise abatement procedures during takeoff and approach, more stringent ATC procedures caused by increased traffic, and emergency and abnormal procedures.

It is apparent from the foregoing examples that the over-all system and its requirements are becoming more complex and that consideration of all of these requirements by the airframe manufacturer is imposing a considerably increased load upon him. In his own specific sphere of activity the aircraft manufacturer is now required to provide, in addition to the normal design, development, and testing facilities associated with airplane design, comprehensive simulator facilities including visual flight simulation and a crew compartment complete with operating displays and simulation of all operationally significant subsystems and environmental influences. This major contribution to the facilities required must be accompanied by a logical and timely program if the process of optimizing cockpit design is to be contained within reasonably economic limits.

Development Facilities and Techniques Used in the SST Program

The SST program provided a unique opportunity for application of systems engineering to the determination of crew requirements. The very nature of this program, with its unusually complex advanced design problems and its government/aircraft manufacturer/airline participation, demanded a fresh approach which considered all aspects of the SST system. System elements affecting the course of the studies on flight station and crew requirements were aircraft performance, handling qualities, and system operation requirements; the aircraft physical environment including weather, turbulence, radiation, and operating temperatures and attitudes; the proposed air traffic control system; and the proposed terminal facilities. Since many aspects of the aircraft environment were incompletely defined, a significant portion of the effort involved programs aimed at providing improved information concerning this environment. In this area, the Federal Aviation Authority (FAA) assumed responsibility for coordinating industry efforts.

An example of a major program which was funded by the FAA and NASA and designed to produce information concerning the SST environment was the air traffic control (ATC) simulation, operated jointly by NASA Langley and the FAA-Atlantic City. In this program, SST aircraft operation, along with other air traffic, was simulated in high-density traffic areas surrounding New York and San Francisco. This program is described in Ref. 1.

Although the FAA coordinated studies defining the aircraft operating environment, the primary responsibility for definiton and design of the aircraft system remained with Lockheed. In this role, it was necessary for Lockheed to define the problems to be resolved, pull together all of the information available as the result of related programs conducted throughout the aviation industry, formulate a program aimed at producing the additional information required as the basis for system design, and secure the cooperation of the most qualified personnel available, representing a broad cross section of industry experience, in helping to develop and evalute the new concepts required for the SST design. This latter step proved particularly valuable as a key to resolving many problems in the flight operations area. Chief technical pilots of the major airlines as well as Air Force, NASA, and FAA personnel participated in several programs, offering their experience both in helping to determine the direction in which each program should be aimed and serving as members of the team formed to participate in each program and to evaluate the results obtained. Their recommendations were of significant value in assuring that the resulting design would be compatible with operational requirements.

Definition of crew and flight station requirements for the SST depended heavily upon simulation of the operating characteristics of the airplane since, aside from some military experience, there was no direct operating experience upon which to draw. As a result, it was necessary to develop new facilities or to adapt existing facilities to the task of simulating the SST. Some of the major facilities used in the SST program are discussed in the following paragraphs.

Lockheed Engineering Flight Simulator

The flight simulator played a much more important part in the SST program than has been customary in past aircraft

Fig. 1 SST flight simulator.

development programs. The aircraft differed so greatly from current civil jets in size, speed, altitude range, and design mission that simulation was literally the only method available for examination of airplane/pilot compatibility from the standpoints of performance, handling qualities, crew workload, and flight station design requirements. For this reason, it was necessary to build an SST flight simulator very early in the development program and to use this simulator continually as a fundamental tool in development of the aircraft.

Lockheed's engineering flight simulator, located at the Rye Canyon Research Laboratory, is shown in Fig. 1. This simulator duplicated the basic SST flight station configuration including the pilot's station and essential flight instruments, displays, and controls. The simulator cab was mounted on a platform giving partial motion in pitch. The simulator provided a variable force-feel control system as required for development and evaluation of flight control system characteristics such as breakout forces, control sensitivity in terms of both force and motion, and control harmony.

Flight simulator computer facilities permitted programming the simulator to operate either in the takeoff/approach/landing regime or, alternatively, in the climb/cruise regime. The moving belt terrain model used in the simulator visual system is shown in Fig. 2. The visual system, which is also computer-programmed to match the flight condition of the airplane, provides either a wide screen display, as shown in Fig. 1, or, with the aid of a TV monitor and a collimating lens-a display for the pilot only. The TV display provides im, proved depth perception and is more valuable when cab motion is used.

NASA Ames

Simulator facilities at Ames include several with motion systems whose capabilities greatly exceed those available elsewhere. For tasks requiring extensive motion studies, these facilities provide the only alternative short of in-flight simulation.

Fig. 2 Visual system terrain model.

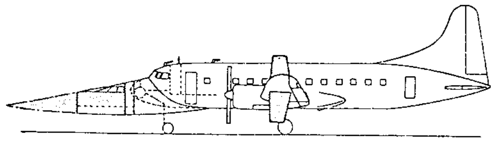

Fig. 3 Cornell total in-flight simulator.

NASA Langley

As previously mentioned, simulation facilities at Langley were combined with the FAA, ATC simulator at Atlantic City in a joint FAA-NASA program aimed at determination of the ATC system on SST design requirements and the effects of the SST on ATC system requirements.

Cornell Aeronautical Laboratories

In-flight simulation capability required for evaluation of SST handling qualities and of pilot workload in real-life environment was provided by a six-degree-of-freedom simulation of the SST incorporated into a Cornell B-26 airplane. This program provided a valuable supplement to the results of ground-based simulator studies, which could not have been obtained in any other way prior to first flight of the SST. Its primary advantage was that it substituted real traffic, weather (including wind shears and turbulence), accelerations, visual cues, and other factors for the artificial cues used in ground-based simulation, thus serving not only to provide additional information but also as a cross check on ground-based simulator results. Although the validity of any in-flight simulation decreases with increased turbulence, the ability of the Cornell simulator to provide a reasonable simulation of SST handling qualities in moderately rough air was a definite asset. A more sophisticated in-flight simulation system, which is being developed by Cornell Aeronautical Laboratories for use on future large aircraft programs, is illustrated in Fig. 3. This airplane, a conventional turboprop Convair, mounts the cockpit of the vehicle being simulated on the nose of the simulator airplane, adding considerably to the realism and value of the simulation. The airplane also incorporates variable lift and side force features which will further increase the validity of the simulation.

University of California Fog Chamber

In this facility, illustrated in Fig.4, a fog-generation system is capable of producing fog of any desired intensity. Approach lights, as well as runway lights, have been installed and a tramway system permits observers in a simulated cockpit to approach the simulated runway on a fixed $2\frac{1}{2}°$ glide path. Operation of this facility is sponsored by the FAA for research into airport lighting requirements. Some results of this program are reported in Ref. 2. This facility also provided a valuable tool for verification of concepts of visual requirements under simulated category II landing conditions. Studies made in the fog chamber confirmed the importance of adequate over-the-nose vision, considering both zero wind and cross-wind conditions, as well as the value of the horizontal

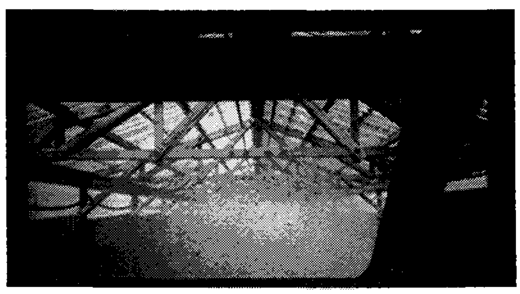

Fig. 4 Fog chamber.

reference provided by a flat glare shield. These studies, together with laboratory work defining light transmission losses as a function of windshield angle of incidence, were responsible for development of the Lockheed Weather-Vision nose concept, Fig. 5, adaptations of which have since been applied to the U. S., British, and Russian SST designs.

SST Flight Station Mockup

As in any aircraft development program, the SST flight station mockup, illustrated in Fig. 6, proved an invaluable tool in the development and evaluation of new concepts, solution of design problems, and performance of crew workload studies.

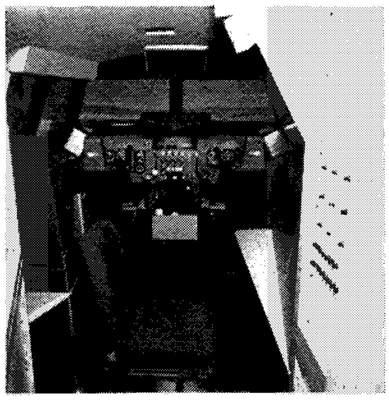

Fig. 6 SST flight station mockup.

Some Results of the SST Development Approach

Although the general approach to determination of flight station requirements and the major facilities used in the SST program have been described, a few examples of the results of this process may be informative.

Visibility Requirements

Visibility standards in effect at the beginning of the SST program[3] expressed the required visibility in terms of vision angles. Although adequate for conventional aircraft, these standards did not cover the special problems posed by an SST, with its higher approach deck angles, long pointed nose, and increased angles of incidence through a fixed windshield. Although a start toward modifying those requirements had been made[4] much additional work was obviously needed.

Preliminary studies of SST configurations revealed the necessity for replacing vision angle requirements by requirements covering the amount of ground the pilot needs to see under the low-visibility approach condition. Fog chamber studies revealed the importance of providing a horizontal glare shield reference and of assuring undiminished visibility under cross-wind conditions. Laboratory studies of light transmission losses established practical limits of incidence angles. These investigations resulted in the establishment of a new set of "rational" visibility requirements, which were presented in Ref. 5. Mockups of several proposed SST nose configurations were constructed and swung on a "high ride" in which airplane cockpit height and pitch and yaw attitudes could be duplicated. Evaluation of these configurations by company and industry pilots quickly revealed that no fixed canopy configuration could meet the requirements. As a result the Weather-Vision nose configuration previously mentioned was adopted.

Instruments, Controls, and Displays

The visibility requirements previously mentioned, coupled with the airplane pitch attitude on approach, required lowering of the instrument panel to provide the necessary visibility. Another basic requirement, adopted after consultation with leading industry pilots, was that the control wheel and the pilot's hands should not obscure any of the basic flight instruments considering wheel angles normally used during approach. This resulted in development of the "yeel" illustrated in Fig. 7. This solution to the instrument visibility problem was evaluated by industry pilots both in the Lockheed Rye Canyon simulator and in a simulator at NASA Ames. Simulator studies, particularly in the climb/acceleration area, showed the need for better incremental trim control, resulting in replacement of the conventional "beeper" switch by the proportional trim control.

Rye Canyon simulator studies also revealed a problem (as did the FAA/NASA ATC simulator program) in intercepting and holding desired cruise altitude. A tentative solution, developed at Rye Canyon, was to increase pitch attitude sensitivity at high altitude. Simulator evaluation, both at Rye Canyon and at NASA Langley, confirmed the effectiveness of this solution, although problems of mechanization were not completely resolved. These studies were validated later when the B-70 flight test program began.

Studies of takeoff climb and noise abatement procedures showed that a constant pitch attitude technique was simple to fly for both normal operation and with an engine failure and, in addition, that it could be varied as desired to put the airplane at the optimum speed/altitude condition for passing over any noise-sensitive area. Techniques for flying sonic boom profiles were also studied. It was found that, although flight director or other guidance was needed in order to follow optimum profiles without undue workload, simplified profiles could be flown without such guidance. Although these profiles involved some increase in fuel required, the penalties were small enough to be considered acceptable for cases where the normal guidance system failed.

Mockup and simulator studies pointed out the desirability of eliminating controls and selectors from the instrument panel and mounting them, together with the most frequently used navigation and communications controls, on a remote control panel. This panel was required to be within easy reach of either pilot, to require minimum head and eye move-

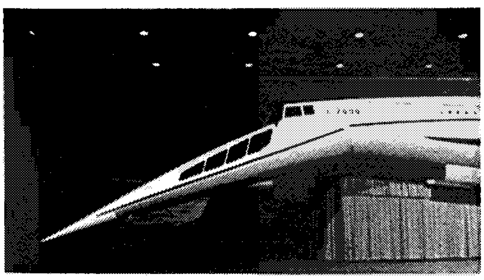

Fig. 5 SST weather-vision nose.

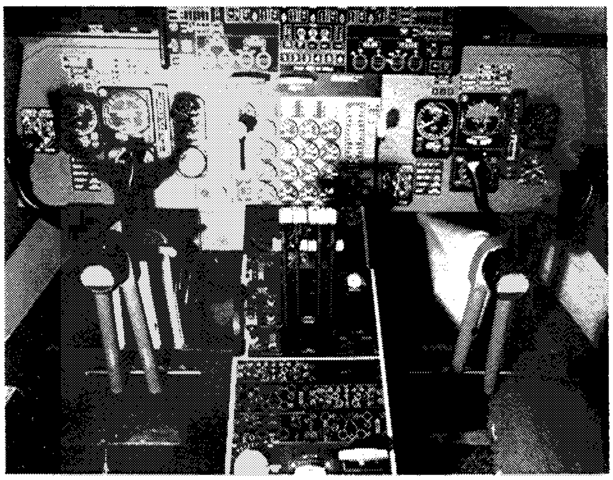

Fig. 7 SST flight instrument panel and yeel.

ment for the pilot (either looking outside or at his flight instrument panel), and to be located so that either pilot would be aware of any new selections being made by the other. The resulting glareshield mode selector panel is shown in Fig. 7.

The all-weather landing requirement for the SST was a deciding factor in the early choice of a vendor for the automatic flight control system because of the need for early and controlled integration of the many subsystems involved. A development and simulator program was defined to be carried out jointly with the selected company. As a result of this joint program, the equipment design format was optimized at a very early stage and the touchdown performance and reliability of the automatic landing system predicted to be of the required levels for at least category IIIA operation. The definition of the role of the pilot during approaches in weather at or below category II limits, however, was not fully resolved, and this aspect of all-weather operations is one which still requires more research and development work before safe and reliable operation is achievable in lower than present weather limits.

Development Plans for New Commercial Aircraft Designs

The lessons learned during the development of the SST cockpit and associated subsystems have been applied in formulating the development plans for our proposed subsonic commercial jet family of aircraft. These plans will emphasize the following factors in order to arrive at the best possible designs.

Simulator Facilities

These facilities will be similar to those described earlier in the paper. More emphasis will be given to the ability to simulate all significant subsystems concurrently as the result of SST experience, showing that this capability is essential to the development of optimum procedures for normal, abnormal, and emergency operation and of the displays and controls required to support these procedures. SST simulator experience also clearly points out the need for providing a "standard" airplane against which to compare the airplane being developed. The reason is that any simulator, no matter how good, still requires extrapolation on the part of the evaluation pilot to relate the characteristics of the simulated airplane to those of the real airplane in flight. Therefore, in order to assure that his "calibration" is not slipping, he needs, periodically, to be able to fly a standard airplane on the simulator. This airplane must be one in which he has had in-flight experience so that he can relate this experience to what he sees on the simulator and adjust his ratings of the simulated airplanes accordingly. In the SST/B-26 program, this calibration was provided by switching back to the basic B-26 as required. In the SST Rye Canyon simulator program, YF-12 characteristics were simulated to provide a unique side-by-side comparison with the simulated SST. In new subsonic commercial jet programs, a representative present-day jet will be simulated for comparative purposes.

Increased subsystems simulation and programming of a current commercial jet for comparison will both increase required computer capacity, but it is felt that this is fully justified by SST experience. The simulation facilities will again include a visual capability that will emphasize operation to touchdown with a capability to represent variable texture fog conditions by synthetic means. Simulation will cover the total flight envelope.

Simulator Flight Station

The simulator flight station will eventually include all of the controls, displays, equipment, and furnishings to be found in the cockpit. The controls and displays for systems that contribute to the pilot's workload, particularly in abnormal or emergency situations, will be operable. Others will be represented by decals, as in the cockpit mockup.

As new ideas for system control/display panels are developed, trial installations of borrowed or prototype units will be made for evaluation. In cases where several candidate competitive products are available, trial installations of each will be made for evaluation by company and airline pilots. The result will be a simulator flight station which develops along with the airplane design and which most effectively supports design development work.

Industry cooperation, which proved valuable during the the SST development, will be sought and encouraged. The maximum use of the results of government and industry studies and programs will be made. In particular, airline participation at the earliest stage is regarded as essential.

The major tasks in the development of the cockpit and associated systems will be reduction in crew workload and all-weather operation system development.

Crew Workload Studies

Crew workload will be evaluated in all phases of flight and during normal, abnormal, and emergency conditions. Among the items for consideration are: general cockpit arrangement, complexity and number of systems, communications requirements, ATC procedures requirements, operation in congested traffic areas—airways and terminal, and incapacitation of one crew member. Methods will be developed of reducing crew workload in areas such as collision avoidance, system monitoring, system normal and abnormal operation, emergency procedures, navigation, and communications.

All-Weather Operation

All weather operation studies and assessments include the following tasks: 1) Assess new display techniques associated with terminal area navigation, including all-weather landings and takeoffs. 2) Assess the effects of malfunctions of the autopilot, flight director, autothrottle, or other elements of the flight control system on the ability of the pilot to take over the control of the aircraft safely, particularly during the the terminal phase. 3) Assess new operational techniques and establish optimum crew procedures with separation of crew workloads associated with terminal navigation and all-weather landings and takeoffs. 4) Determine the optimum format and presentation of failure warning, mode selection, and mode annunciation. 5) Integrate cockpit controls, switching, displays, failure warning, annunciators, and other elements associated with the flight control system. 6) Assess crew reaction to the dynamic performance of the autopilot, flight director, autothrottle, and other elements of the flight control system when operated as part of a closed-loop dynamic system including aircraft dynamics.

This next generation of subsonic aircraft produces a challenge in a number of respects associated with crew requirements. For example, the development task for avionic and controls subsystems is now such that it is essential to appraise the interdependence of many individual subsystems and the pilot from a safety and performance viewpoint prior to the design freeze of the subsystem and cockpit configuration. Perhaps the major task in this area is all-weather operation since this generation of aircraft will be one of the first to be specifically designed to achieve regular operation in weather minima near to zero. There have been many papers and discussions on the role of the human pilot in an aircraft capable of low-visibility operation but no mutually agreeable definition as yet. During the development of these new aircraft, we will be faced with defining a practical solution to this problem at the outset of the design. We are not convinced that all-weather landing concepts involving the pilot solely as a monitor and using present-day airborne instrument displays will be adequate for safe operation below 100 ft, and it is upon this aspect of all-weather landing that we intend to concentrate considerable effort. The commitment to provide category II and III operations is one which must be taken as seriously as meeting the other major requirements of field length, range/payload, and operational costs.

In the general area of cockpit instrumentation and displays, we believe there is considerable potential for improvement and, without prejudging the cockpit arrangement that will finally be developed, we believe that we may be on the brink of a breakthrough in cockpit instrumentation design which would be acceptable to the airlines. The simulator facilities we will employ on these new aircraft, coupled with the support and advice that we will solicit from the airlines, will insure that the best decisions are made, in a controlled environment as near the real world as possible.

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