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A PRA CASE STUDY OF EXTENDED LONG TERM DECAY HEAT REMOVAL FOR SHUTDOWN RISK ASSESSMENT*

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ABSTRACT

A Probabilistic Risk Assessment (PRA) of the Experimental Breeder Reactor II (EBR-II), a Department of Energy (DOE) Category A research reactor, has recently been completed at Argonne National Laboratory (ANL). The results of this PRA have shown that the decay heat removal system for EBR-II is extremely robust and reliable. In addition, the methodology used demonstrates how the actions of other systems not normally used for decay heat removal can be used to expand the mission time of the decay heat removal system and further increase its reliability. The methodology may also be extended to account for the impact of non-safety systems in enhancing the reliability of other dedicated safety systems.

I. EBR-II

EBR-II is a DOE Category A research reactor located at ANL West in Idaho. It is a pool design 62.5 Mw-thermal Liquid Metal Reactor (LMR), which generates 18.5 Mw-electric power which is used for site power with the excess power transmitted to the Bonnyville Power Authority through the Idaho National Engineering Laboratory (INEL) loop. EBR-II has been operating since 1964 and it has been used in a variety of research programs. Currently it is the prototype of the Integral Fast Reactor (IFR) Program. A PRA for EBR-II[1] was begun in 1989 as a result of a National Academy of Sciences recommendation that probabilistic risk assessments be performed for DOE Category A reactors.

II. DECAY HEAT REMOVAL SYSTEMS

Decay heat removal at EBR-II is normally accomplished either by use of the secondary sodium system and balance of plant (BOP) or by use of a dedicated shutdown cooling system. In some situations, a combination of the shield cooling and thimble cooling systems can also be used for decay heat removal.

The secondary sodium system, normally a forced convection system at power, can be operated as a natural convection system at decay heat levels. There are no isolation valves in the primary flowpath. The elevation of the natural convection thermal driving centers for the primary loop (reactor core and intermediate heat exchanger) and intermediate loop (intermediate heat exchanger and evaporators/superheaters) as shown in

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Figure 1 is such that natural convection can be maintained throughout a transition from forced convection flow to natural circulation flow. This transition has been experimentally demonstrated[2]. The balance of plant (BOP) requires only limited electrical power for periodically refilling the steam drum. The steam dump capacity of the BOP is sufficient to allow dumping the full power heat load of the reactor if normal electric power is available.

Figure 1: Primary and Intermediate Sodium Loops

The shutdown cooling system is a natural convection safety system requiring no electrical power or other support systems. The shutdown cooling system removes heat from the primary sodium tank through two natural convection NaK loops to the atmosphere. The primary purpose of this system is the removal of decay heat from the primary sodium when the secondary sodium system is inoperable. The system is one of the EBR-II "sensitive" systems. i.e. it is critical to the integrity of the primary tank and internals and therefore is an engineered safety feature (ESF). In addition to its function as an ESF, the system is also used to accelerate the reactor cooldown rate in conjunction with the main sodium, secondary sodium, and BOP systems.

The shutdown cooling system consists of two identical sub-systems as shown in Figure 2. Each of the cooling sub-systems consists of a shutdown cooler plug, a shutdown cooler nozzle, a NaK-air heat exchanger, and associated piping and equipment. Flow occurs in a closed loop between the heat exchanger and individually mounted L1 and L2 nozzles extending into the primary tank. The heat exchanger cores are mounted in two box assemblies on the outside wall of the reactor building. The natural convection flow of NaK is completely independent of any electrical power and there are no valves in the system. Therefore, flow occurs whenever the bulk sodium in the primary tank is hotter than the outside air. A small expansion tank blanketed with argon gas and part of the NaK/air heat exchanger box assembly permits thermal expansion of the system. The transfer of decay heat from the NaK coolant is accomplished by the natural convection flow of air past a finned-tube heat exchanger. The rate of air flow is controlled by dampers positioned above and below the heat exchanger and by a sheet metal chimney located above the upper damper. The dampers are held closed during normal operation by instrument air acting against spring loaded actuators. In the event of a loss of either instrument air or the continuous power system the dampers will open. If the average bulk primary

Figure 2: *Shutdown Cooling System*

sodium temperature exceeds (710°F), the control system will open the circuit to the air supply solenoid, allowing the dampers to open, air circulation, and full flow in the NaK loop.

An additional system that can be used for decay heat removal at reduced heat loads is a combination of the shield cooling and thimble cooling systems. Originally, the shield cooling system was designed to prevent dehydration of the biological shield. However, the design of the shield cooling system is such that the flow path around the primary tank is similar to those that have been proposed for decay heat removal through reactor vessel auxiliary cooling systems (RVACS)[3] for advanced LMRs. The major difference of these two systems is that the shield cooling system relies on forced convection and therefore electric power while RVACS designs are natural convection.

The shield cooling system cools the reactor shielding and recirculates air through the air-baffle tank surrounding the primary tank inside of the blast shield and draws in air around openings near the nozzles in the rotating plugs and boot seals of the nozzles of the primary tank cover. This cooling is necessary to prevent the concrete shielding from losing its water content resulting in a loss of structural strength and effective shielding. Another purpose of the shield cooling system is to provide circulation of air from the reactor building main floor through the depressed area and the space above the primary tank. The shield cooling system forms an integral part of the reactor building ventilation system and maintains the reactor building pressure at slightly less than atmospheric by exhausting air from the reactor building through the plant suspect exhaust system.

The shield cooling system consists of two recirculation fans, two exhaust fans, manual and automatic dampers, and inter-connecting duct work. An overview of the system is shown in figure 3. The exhaust fans draw approximately 2.36 m^3/s (5000 cfm) of air into the system from the reactor building atmosphere. In addition there is an additional 7.08 m^3/s(15,000 cfm) being recirculated through the air baffle tank which surrounds the primary tank. Cooling of the circulating air in the system is provided both by the once through nature of the exhaust system and by a freon cooing system for the recirculating portion of the system.

The thimble cooling system is a once-through system which aids in maintaining the reactor building pressure at slightly less than atmospheric by exhausting air from the reactor building through the plant suspect exhaust system. The system

Figure 3: Shield Cooling System

consists of two turbocompressor exhaust fans, eight instrument thimbles, intake and exhaust filters, and associated piping as shown in Figure 4. The system removes 0.94 m^3/s (2000 cfm) of air from the reactor building.

The thimble cooling system provides additional cooling of the primary tank. The thimble cooling system was designed to provide cooling for instrumentation located in eight instrument thimbles which penetrate the primary tank. Currently three of these thimbles are used for the neutron detectors and the remaining five thimbles are vacant but can be used for experimental instruments.

III. SUCCESS CRITERIA

Most PRA's only consider decay heat removal for the first 24 hours following an accident. The EBR-II PRA analyzed decay heat removal for a mission time of 45 days and a success criteria of not exceeding a bulk sodium tank temperature of 811 K (1000 °F). The logic for this extension was to include normal shutdowns which last four to seven days and the annual "long" shutdown for major maintenance and upgrades which typically is on the order of 30 to 40 days. During the "long" shutdown, the secondary sodium system (intermediate loop) is drained to allow maintenance on this system. Therefore, during the "long" shutdown, the reactor is essentially in a configuration of degraded decay heat removal capacity in that the normal heat removal path for the reactor is inoperable. The 811 K (1000°F) temperature limit was based on structural considerations of the primary tank and long term limits for fuel cladding integrity. This long term exposure to elevated temperatures was defined as a separate damage class labelled core and structural damage (CSD)[4]. An additional constraint on decay heat removal was it was not considered available for the first 8 hours following a transient. This 8 hour grace period was possible due to the large heat capacity associated with a pool design LMR and assured time for a high reliability of operator recovery actions in the event that the shutdown cooler system louvers did not operate automatically.

The total decay heat removal capacity varies depending on whether the shutdown cooler louvers were open and electrical power was available for the shield and thimble cooling systems. Also electrical power is sometimes used to limit cooldown by applying a reversed voltage to the secondary EM pump to retard secondary sodium flow . Table 1 and 2 summarizes each of these respective heat removal capacities and sources.

Figure 4: Thimble Cooling System

Table 1: Decay Heat Removal Capabilities

SYSTEM	MODE	HEAT REMOVAL
BOP	Natural Circulation	2350-3800 kW
	Retarded	As Required
	Minimum Retarded	45-135 kW
Shutdown Coolers	Louvers Closed	60 kW
	Louvers Open	360 kW
Shield & Thimble Cooling	Forced Convection	130 kW
	Radiation	25 kW

Table 2: Sources of Post Shutdown Heat

SYSTEM	HEAT ADDITION
Primary Pumps	200 kW *
Core Decay Heat	Varies with time
Basket Heat **	<100 kW

* If energized

** EBR-II stores spent fuel assemblies in the primary tank

A simple lumped parameter heat balance program was used to determine the maximum temperatures reached for a combination of heat removal capacities. This calculation included assumed times for loss of various parts of the overall decay heat removal system. The resulting calculations guided the development of success and failure criteria for decay heat removal. In particular, it was determined that a combination of shield and thimble cooling was sufficient to maintain the primary tank temperature below 811 K (1000°F) after 14 days if at least one of the shutdown coolers had been operating in the interim. Therefore, decay heat removal was divided into short term (8 hours to 14 days) and long term (14 to 45 days). The BOP was separated from the shutdown coolers and considered separately giving rise to three sets of conditions as shown in table 3.

Table 3: Success and Failure Criteria for Decay Heat Removal (DHR)

Top Event	Success Criteria	Failure Criteria
BOP decay heat removal maintained	Heat sink available within 8 hours and maintained for 14 days	Unrecoverable loss of heat sink within 14 days of shutdown
Short term decay heat removal initiated and maintained	One of two shutdown coolers available within 8 hours and maintained cooling for 14 days	Less than one cooler available within 8 hours or DHR cannot be maintained for 14 days
Long term decay heat removal maintained	One of three methods, BOP, shutdown coolers, or shield and thimble cooling available from 14 days to 45 days	All DHR systems fail in 14 to 45 days

This extended analysis showed that the dedicated safety systems were sufficient but that additional reliability could be demonstrated by including the secondary sodium/BOP and the shield/thimble cooling systems where applicable. The results of the EBR-II PRA showed the decay heat removal failure rate to be 8.4 x 10^{-9}. The improvement in reliability was approximately one and a half orders of magnitude compared to a case considering only the shutdown coolers (1.5 x 10^{-7}). The relative effect was even more dramatic for specific accident sequences, especially those involving either degraded decay heat removal capability due to the initiating event or the "long" shutdown case where the secondary sodium is drained for maintenance. In these scenarios, the improvement was several orders of magnitude. For example, one initiating event is an assumed liquid metal fire within the containment due to a rupture of the NaK piping of a shutdown cooler. In this case, the operator may be unable to determine if the fire is due to the NaK leak or a secondary sodium leak and by procedure would then dump the secondary sodium. The decay heat removal would then be entirely dependent on the remaining shutdown cooler unless the secondary sodium system could be recovered. However, after 14 days, use of the shield and thimble cooling would change the success criteria for long term decay removal from one of one systems to one of two systems.

IV. CONCLUSIONS

The lesson learned in this study was that the natural circulation systems and the high thermal inertia associated with the Integral Fast Reactor designs provide an extended decay heat removal capability without the need of supporting systems such as electrical. However, this high level of reliability can be shown to be even higher by considering the decay heat removal capability of non-safety systems. To neglect these systems may result in misallocation of resources that may otherwise be used to reach the highest optimum level of reliability and safety.

Reactor support systems are often divided for regulatory purposes into two classes, safety and non-safety. The designation "safety" and/or" important to safety" often carry additional regulatory requirements. In typical safety assessments, only those systems with a safety designation are considered in the analysis. Other systems, which are present either for investment protection or operational requirements, are not considered as part of the safety response of the plant except as a part of extraordinary measures in the recovery phase of an accident sequence. This narrow focus on safety systems may result in a distorted representation of the actual level of plant safety. The Experimental Breeder Reactor-II Probabilistic Risk Assessment (EBR-II PRA), which considered all major reactor support systems, demonstrated the added margin present in the plant due to non-safety supporting systems.

V. REFERENCES

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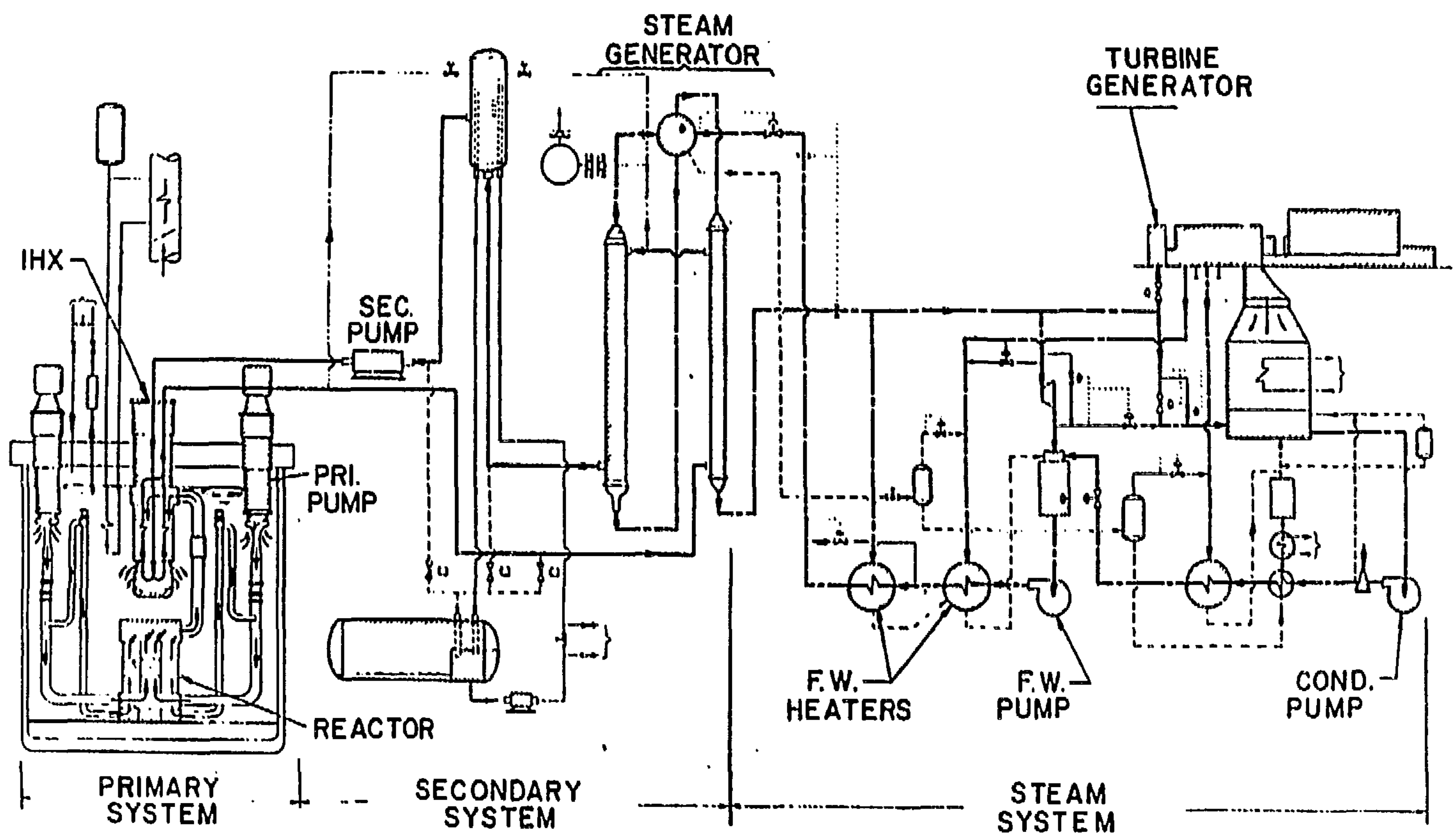

Fig. 3.7. EBR-II Systems (Simplified)

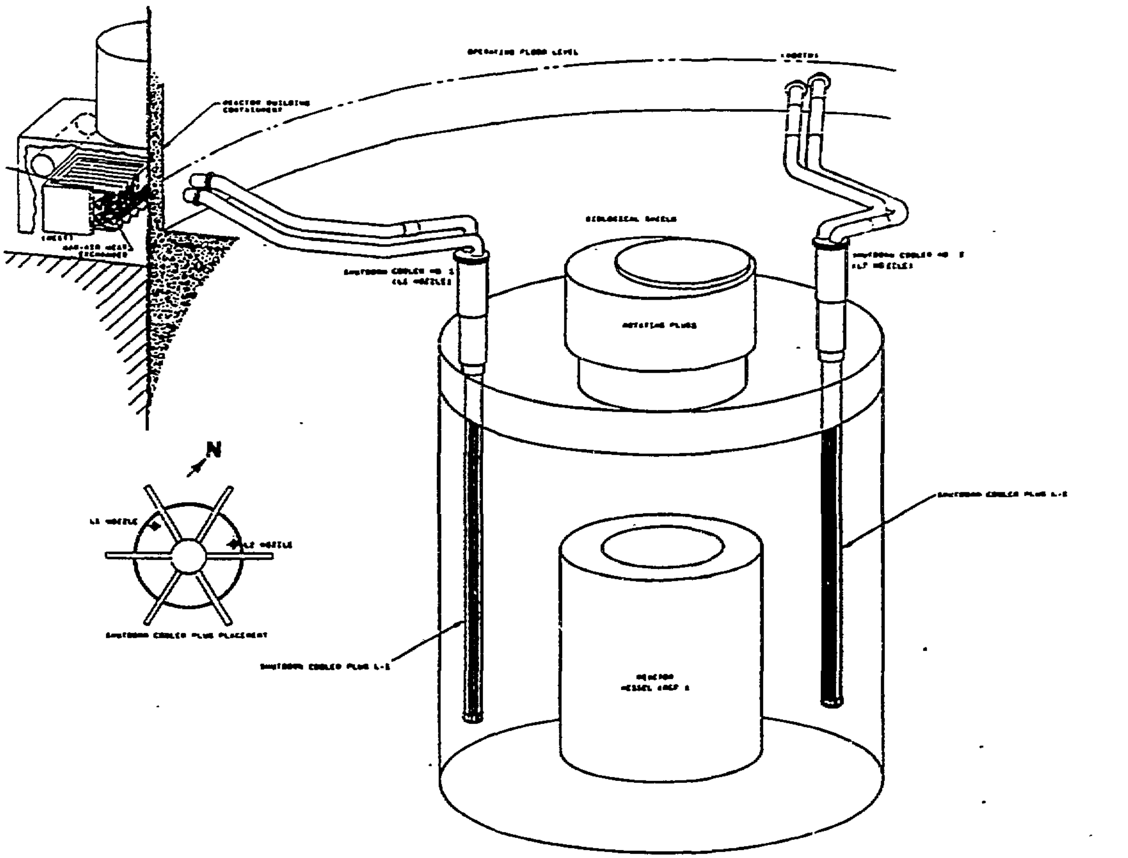

Fig. 6.5. Shutdown Cooling System

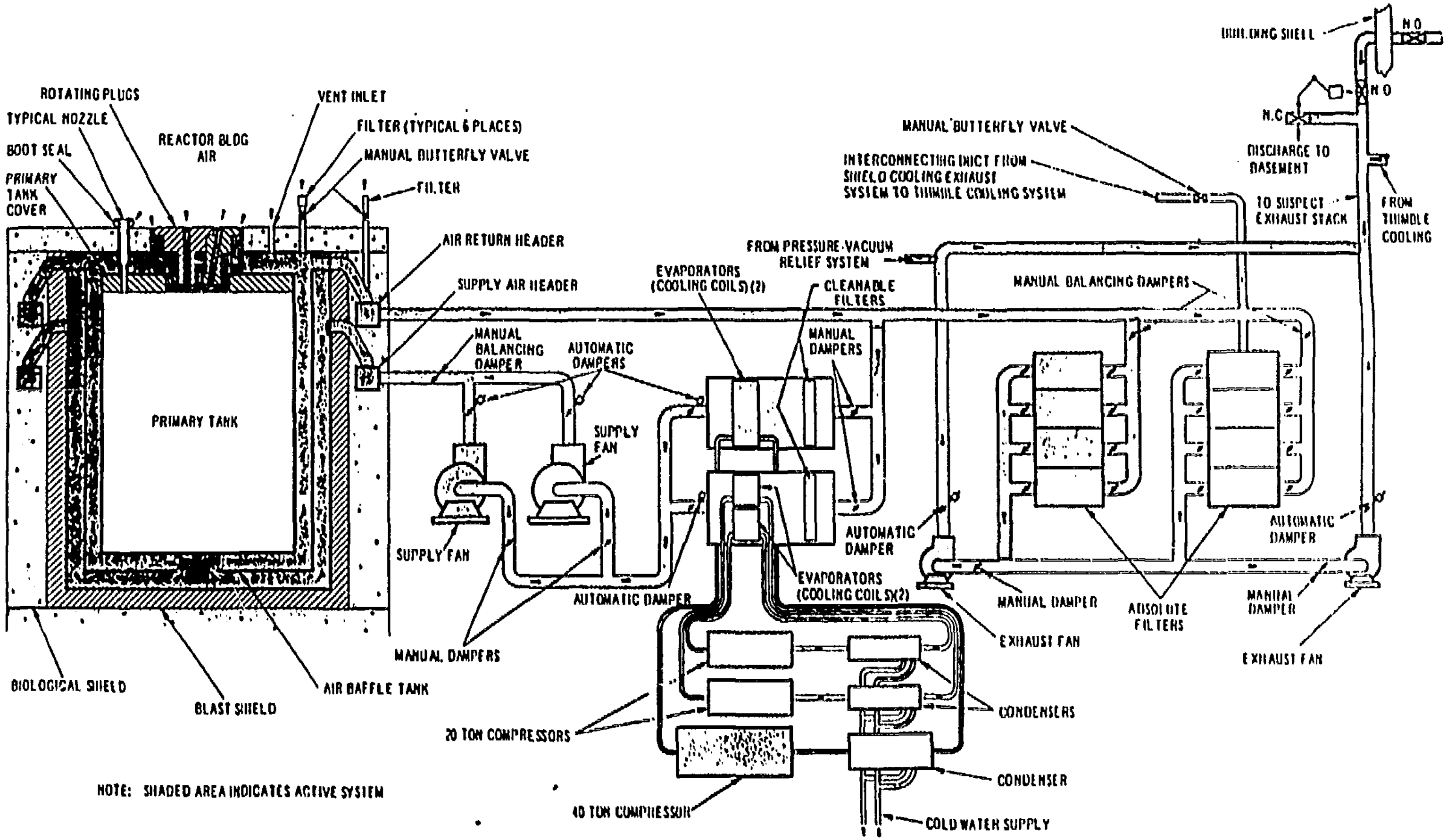

Fig. ~~6.6~~ 3. Shield Cooling System Pictorial Flow Diagram

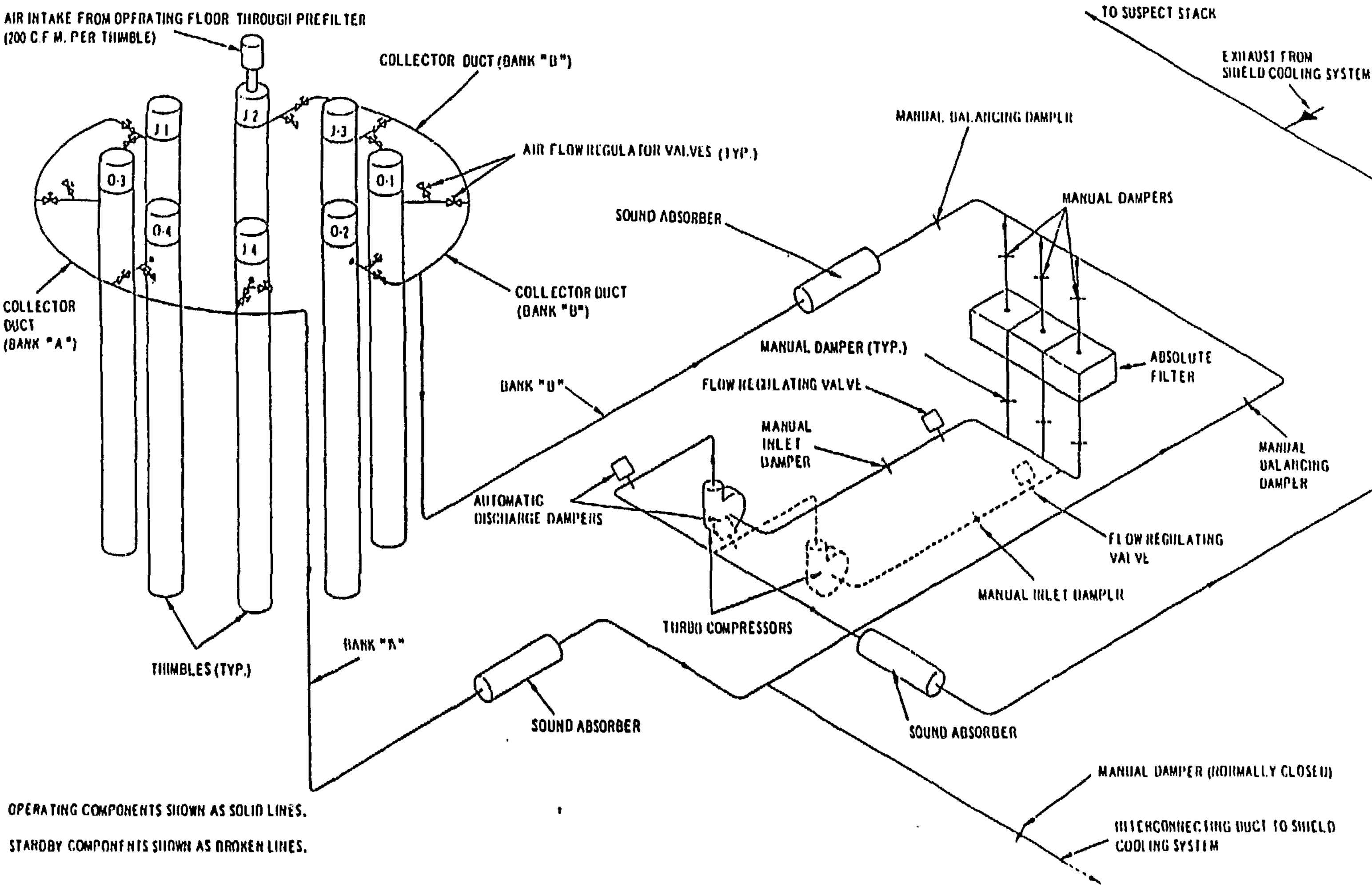

Fig. ~~6.7~~ 4. Instrument Thimble Cooling System Flow and Equipment Diagram